CHAPTER 2

METHODS OF OBSERVATION

2.1 INTRODUCTION – THE HYDROLOGICAL CYCLE AS THE SUBJECT OF OBSERVATION

Water is found on Earth in significant amounts in all three of its physical phases: liquid, solid and gaseous. It is also found in all three of Earth's major environments that are readily accessible to humans: the atmosphere, the seas and oceans, and the land masses. As water can readily move from one environment to another and can change from one phase to another in response to its environment, it is a dynamic medium in both space and time. The Earth's system of repositories for the storage of water and the multitude of paths among the many repositories has been conceptualized as a cycle, as shown in Figure I.2.1. The science of hydrology has not traditionally encompassed the entire hydrological cycle, but has been limited to the land portion of the cycle and its interactions with the oceans and atmosphere.

Because humankind spends a predominant amount of time on the land surface and water is both a necessity for life and a potential hazard to it, hydrological knowledge is valuable in providing for our continuity and well-being. One traditional means by which hydrological knowledge has been accumulated is through measurement of the storage and flow of water at distinct points in time and space. Such measurements, also known as data, are analysed and synthesized to generate hydrological knowledge or information. Volume II of this Guide deals with hydrological analysis.

Two of the basic equations that describe the physics of the hydrological cycle are also pertinent in describing the systems that are used to make measurements of its transient properties: (a) the equation of continuity of mass; and (b) the equation of continuity of energy. For example, one form of the equation of continuity of mass:

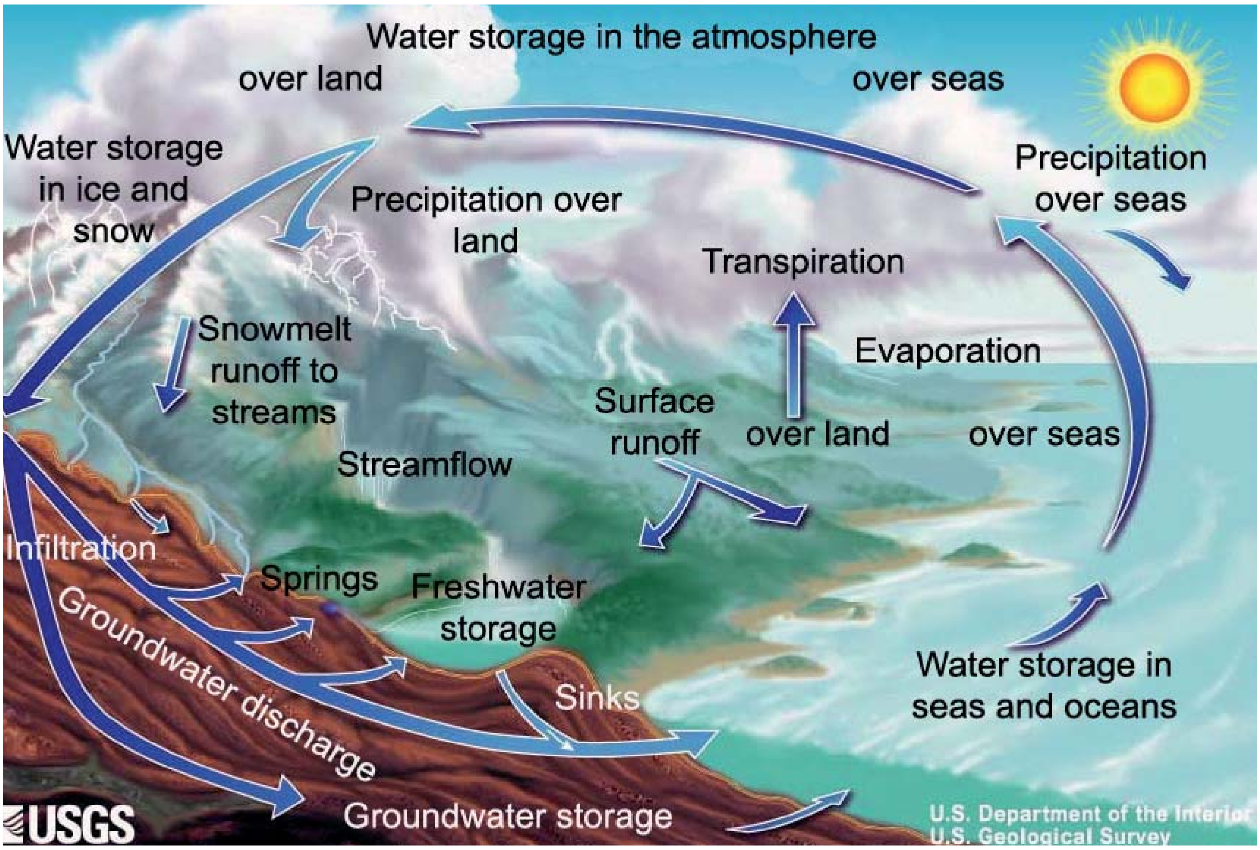


Figure I.2.1. The hydrological cycle

$$Q = AV \qquad (2.1)$$

often serves as the basis for the determination of the flow rate in a stream or canal. In this equation, Q is the instantaneous rate of flow through a cross-section of channel with area, A and average flow velocity, V. Traditionally, flow rate, also known as discharge, could not be measured directly for streams of even a modest size. A cross-sectional area, however, can be measured by sampling its spatial dimensions, and velocities can be sensed by the use of current meters. Thus, the use of this equation, described in detail in Chapter 5, has permitted determinations of the rate of discharge of even the largest rivers of the world.

Another example of the role of the equation of continuity of mass can be found in the observation of evaporation of water from a lake surface. In this example, the equation takes the form:

$$P + I - O - E = \Delta S \qquad (2.2)$$

where P is the amount of precipitation that falls onto the surface of the lake during a period of observation, I is the inflow of surface water and groundwater during the period, O is the outflow of surface water and groundwater, E is the quantity of water evaporated from the surface of the lake during the period, and ΔS is the change in the volume of water in the lake during the period.

Precipitation can be measured according to the techniques described in Chapter 3; inflows and outflows can be measured using techniques described in Chapters 4, 5 and 6; changes in the lake contents can be computed by relating the lake-surface elevations at the beginning and the end of the observation period to the respective contents at those times; and water-level measurement is discussed in Chapter 5. By measuring or otherwise observing four of the five terms in equation 2.2, the fifth, evaporation, can be computed algebraically.

Systematic hydrological observations are at the very core of the development of databases, information and knowledge required for the effective management of water resources. This chapter discusses a number of subjects that are fundamental to the operation of hydrological and meteorological observing networks and to the production hydrological information.

The chapter provides an overview of hydrological standards and codes, accuracy of measurements, concepts of network planning, methods of observation, measurement of physiographic characteristics, the role of hydrological data in information systems and the linkages to sustainable development. Some of these subjects are discussed in greater detail later in this Volume. Where this is the case, cross-references are provided.

2.2 WATER RESOURCES INFORMATION SYSTEMS

2.2.1 Need for data and information

The report of the International Conference on Water and the Environment (ICWE), held in Dublin in January 1992 (United Nations, 1992*a*), provides a compelling assessment of the importance of water resources to the world's environment and to its economy. Its specific policy statements highlight very effectively the role that hydrological services should play in achieving goals related to sustainable development. ICWE addressed the following issues:

(a) Integrated water resources development and management;
(b) Water resources assessment and impacts of climate change on water resources;
(c) Protection of water resources, water quality and aquatic ecosystems;
(d) Water and sustainable urban development and drinking water supply and sanitation in the urban context;
(e) Water for sustainable food production and rural development, and drinking water supply and sanitation in the rural context;
(f) Mechanisms for implementation and coordination at the global, national, regional and local levels.

Volume II, Chapter 3, reviews the evolution of integrated water resources management and provides examples of best practices. The nature of the information that will be required to meet the needs of integrated water resources management is difficult to project. Perhaps, the best ideas can be gathered from considering recent trends in water management (2.2.4). Since data are gathered for the use of water managers, whether in government or private agencies, changes in the way water is managed will influence the data and information demands.

The impacts of these changes may include:

(a) Growing competition for water, resulting in a higher value being placed on available supplies

and, ultimately, goods and services being redefined in terms of their water content – this could be exacerbated by declining water availability and quality in many areas;
(b) Economic pressures resulting in more user fees, cost sharing and local financing of water programmes, with a concurrent shift in emphasis from water development activities to environmental programmes and demand management;
(c) Increased focus on water conservation and reuse in all phases of project development – in some areas, reclaimed water now costs less than freshwater supply;
(d) Environmental legislation designed to hold polluters and users accountable for their impacts on available supplies;
(e) Legal measures to ensure that users and water managers justify their needs, uses and management practices, and that increased priority be accorded to environmental water uses (for example, fish and wildlife habitat) versus the traditional economic uses (for example, agriculture and industry);
(f) Emphasis on basin and regional water planning as a means of resolving transboundary issues and disputes.

These trends indicate that greater coordination of data-collection efforts will be required to meet the needs of water managers in the future. Water management is becoming more integrated across disciplines and specialities; therefore, compatible data on quantity and quality of surface water and groundwater, and on specific basins and regions will be required. Current problems related to data accessibility, compatibility and reliability will have to be resolved to meet these needs. In addition, water management challenges are closely linked to those of environmental management or ecosystem management. Therefore, an increasingly holistic management approach is required.

While many users will continue to need data for design and analysis purposes, increased attention must be paid to the need for comprehensive regional surface-water information that can be applied to many different kinds of water issues and problems. This means that overview information, fact sheets and summaries, surface-water and precipitation mapping, hydrological assessments of basins and regions, and water information relevant to the assessment of water quality and groundwater problems must be available. The use of real-time water data will continue to grow to serve many needs.

2.2.2 Hydrological information systems

This Volume of the Guide deals with the field activities of operational hydrology. However, the data that are generated by the field activities are of little or no value if they cannot be readily and confidently accessed by the potential data users. Operational hydrology within a given Hydrological Service can be considered as an information system providing a conceptual basis for the development of proper approaches, which ensure that the right data are available in the right form at the right place and time. Figure I.2.2 depicts the elements of a hydrological information system. Ideally, the information system is embedded in a natural sequence of actions and decisions that begins with the perception of an opportunity and culminates in the implementation of decisions that maximize the net positive impacts of the opportunity.

A hydrological information system combined with a suite of numerical models – physical, statistical or socio-economic – comprises a decision support system. With the decision support requirements firmly in mind, the designer of the information system can specify the procedures to be used to analyse the hydrological data. These data-analysis technologies may be any one model or a combination of models that account for the probabilistic, stochastic or deterministic natures of the hydrological phenomena of interest. Volume II of this Guide (in particular Chapters 5 to 7) discusses many of these data-analysis technologies.

The actual data collection can begin at this point in the sequence, and it is also at this point that feedback, represented as dashed arrows in Figure I.2.2, begins to take place. All of the previous steps have been based on a specific level of knowledge about the hydrological conditions of interest. As data are collected, this level increases, and new data-analysis techniques and new network designs may become appropriate. Guidance on data collection is given in 2.5.

From Figure I.2.2, it is possible to see that quality assurance is an integral phase of the information system that is relevant throughout the continuum from field activities to the dissemination of data and information. Owing to its pervasive nature, quality-assurance guidance can be found throughout this Volume.

No discussion of information systems is complete without mention of data management systems. The information contained in a robust data-management system is available, not only for the uses for which

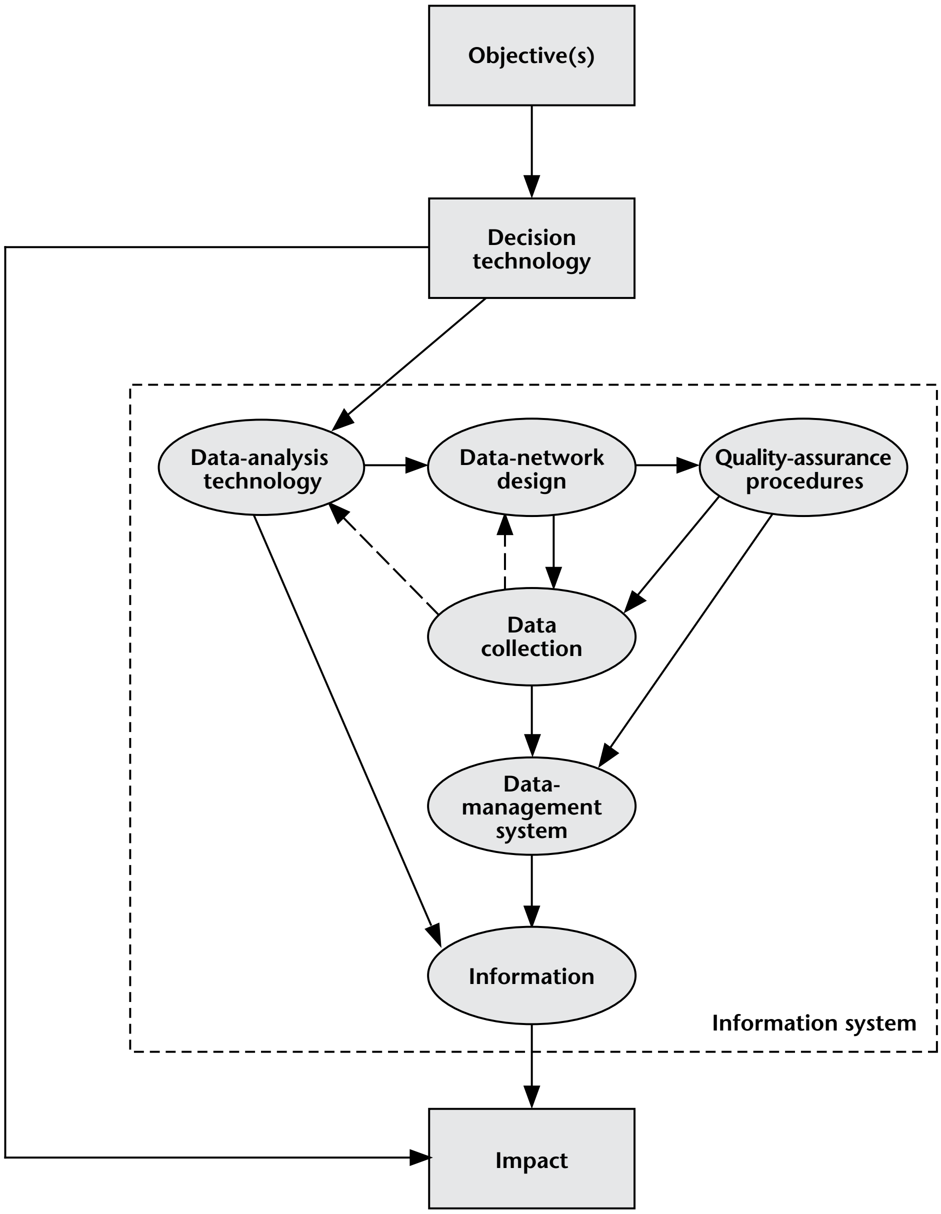


Figure I.2.2. Components of a hydrological information system

the data were collected originally, but also for a multitude of uses that may never have been anticipated. However, with robustness comes a price. The options inherent in robust systems tend to make them difficult to use, as more training is required. This represents the first portion of the price. This part of the cost can be minimized by user-friendly systems designs. The second cost factor is the potential loss of information that robustness entails. As a data-management system cannot be all things to all people, compromises must be made, which usually result in data compaction and loss of data attributes. To reduce such loss, subsystems that retain more objective-specific data can be appended to the robust, central system. Such systems are discussed in Chapter 10. Current technology also allows the development of distributed hydrological information systems having searchable metadata. Provided that computer security matters are fully considered, such virtual data systems provide an effective and robust means of accessing data and information required for decision-making.

The ultimate product of the information system is obtained by processing the data through the same data-analysis technology that was initially crucial in the design of the data network. The sequence culminates by integrating the hydrological information into the decision process for which it was designed to have an optimal impact. The key to obtaining this optimality is the compatibility among the decision technology, the data-analysis technology and the data network.

A well-designed information network contains synergism that is derived in three ways. First, information is a commodity that is not destroyed by its use. Thus, if properly preserved, it can be made available at minimal cost for many uses not anticipated at the time of its collection. Secondly, information can be used to improve understanding of hydrological processes. By improving process understanding, both the information content of the existing data and all future data are increased. Thirdly, synergism evolves by taking advantage of the accomplishments of others. New approaches and technologies for the design of information systems, like the data they contain, are recyclable commodities.

2.2.3 Uses of water resources information

Hydrological or Hydrometeorological Services or related agencies have been established in countries for systematic water resources data collection, archiving and dissemination described elsewhere in this Volume. Their primary role is to provide information to decision makers on the status of and trends in water resources. Such information may be required for the following purposes (WMO/UNESCO, 1991):

(a) Assessing a country's water resources (quantity, quality, distribution in time and space), the potential for water-related development and the ability of the supply to meet actual or foreseeable demand;
(b) Planning, designing and operating water projects;
(c) Assessing the environmental, economic and social impacts of existing and proposed water resources management practices and planning sound management strategies;
(d) Providing security for people and property against water-related hazards, particularly floods and droughts;
(e) Allocating water among competing uses, both within the country and cross-border;
(f) Meeting regulatory requirements.

Most frequently, water resources information has been collected for a specific purpose, such as the design of a hydroelectricity scheme. However, increasing competition among users for scarce water requires that resources be managed in an integrated fashion, so that the interactions among several projects and users may be understood. This places a much greater burden on the suppliers of water resources information, because a variety of types of information is simultaneously needed, and has to be presented in different forms for different users. This makes it essential that assessment agencies understand the needs of all their users, and not just those with whom they have traditionally dealt. Even more demanding is the need to look ahead to the possible needs of future users of data and to commence collecting the information before an actual demand can be demonstrated with certainty. Therefore, it is necessary that the design and updating of data-collection networks, especially the principal stations, be coordinated to ensure that stations for monitoring the various elements of the water cycle are sufficiently related, both in number and location, to achieve an integrated network (2.4). Such an approach would enhance the information content of the data sets for both current and unforeseen future needs.

With the growing recognition of such issues as global climate change and the environmental impacts of human activities, such as urbanization, there is an increasing emphasis upon the information required as a foundation for sustainable development and management of water resources. Volume II, Chapter 3, describes the rationale for integrated water resources management and presents elements of best practice.

2.2.4 Types of water resources information

The diversity of possible uses of water resources information implies that there is a considerable range of types of data. Conventional water resources information comprises the statistics of a variety of meteorological and hydrological elements. The elements include the following (WMO/UNESCO, 1991):

(a) Precipitation, for example, rainfall, snow and fog drip;
(b) River levels and flows, and lake and reservoir levels;
(c) Groundwater levels;
(d) Evapotranspiration;
(e) Sediment concentrations and loads in rivers;
(f) Water quality (bacteriological, chemical; and physical) of surface water and groundwater.

The statistics include the following:

(a) Mean annual, monthly, or seasonal values;
(b) Maxima, minima and selected percentiles;
(c) Measures of variability, such as the standard deviation;
(d) Continuous records in the form, for example, of a river flow hydrograph.

There is a requirement for both historical and real-time data to cater to the full range of needs from water resources planning to project design and flood warning. Flood or low flow forecasting (Volume II, Chapter 7) may require data to be synthesized for the future by using numerical flow-routing models (Volume II, 6.3.4).

The *Water-resource Assessment Activities: Handbook for National Evaluation* (UNESCO/WMO, 1988) recognizes a number of types of water resources projects for which hydrological information is required, as given in Table I.2.1.

Together, these imply a vast range of water-related data and information that the Hydrological Services and other related agencies may be required to collect and archive. Different countries have different priorities that depend on their level of economic and social development, the sensitivity of their natural environments to disturbance by human activity, and the nature of the physical environment itself, for example, climate, topography and the abundance or otherwise of water.

There are several critical requirements for an effective water resources assessment programme:
(a) Data of high quality must be collected to permit confident statistical analysis;
(b) The data and the information that they provide must be carefully targeted to the requirements of users;
(c) An integrated observation programme, in which measurements of several variables are made simultaneously, is required to provide the greatest total value;
(d) Other forms of information that are compatible with and can be analysed with water resources information should be available;

Table I.2.1. Hydrological information required for water resources projects

Water projects	*Water levels*			*River flow*			*Sediment*			*Water quality*[a]		
	time series	*max*	*min*	*time series*	*max*	*min*	*time series*	*max*	*min*	*time series*	*max*	*min*
Redistribution of water (diversions, intakes, canals)	M	M	M	H	H	H	H	M	M	H	M	M
Redistribution of water in time (reservoirs)	M	M	M	H	H	H	H	M	M	H	M	M
Energy production (hydropower, waste heat disposal)	H	M	M	H	M	H	H	M	M	M	M	M
Water confiners (dams, flood banks)	H	H	M	M	H	M	M	M	M	M	M	M
Water relievers (spill ways)	M	H	M	H	H		M			M		
Quality improvements (water and sewage treatment)				H	M	H	M	M	M	H	H	H
Zoning (flood plain, scenic rivers)	H	H	M	M	H	M	M					
Insurance (flood damage, water quality damage)	H	H		H	H					H	H	
Flow and level forecasts (flood control, reservoir operation)	H	H	H	H	H	H						
Standards and legislation (water quality)	M	H	H	M	H	H				H	H	H

[a] Water-quality parameters are diverse depending on the type of project.
H = High level of priority M = Medium level of priority

(e) An effective system is needed for archiving and disseminating data to ensure that they are not lost or corrupted and that they are made available in a form that enables analysis (Chapter 10).

The above requirements can be met by the application of contemporary technologies – for example, telemetry, to make data available in near-real time – by implementing searchable computer databases, by remote-sensing to collect areal information more effectively and by Geographical Information Systems (GIS) (2.6.7) to provide a means of analysing spatial data. At the same time, new computer storage devices and the use of the Internet make the data more readily available. Nevertheless, technology is not the only requirement, and a trained and well-managed staff is of even more fundamental importance. As financial resources become increasingly limited in many countries, it becomes ever more vital that effective organizational structures are in place to ensure that those resources are used most efficiently.

In addition to the more conventional measurements, there is a growing recognition of the need to measure other aspects of the freshwater environment and of the wider environment in which freshwater is only a single component. These include:

(a) The volumes of water needed for industrial, domestic and agricultural use, and for navigation. These are now significant modifiers of the hydrological cycle in many basins;
(b) Attributes of rivers and required volumes of water related to instream uses, for example, freshwater fishery habitats or recreation;
(c) Watershed characteristics that may be related to hydrology, for example, vegetation patterns, soil moisture, topography and aquifer characteristics;
(d) Environmental concerns, for example, eutrophication of lakes and damage to natural freshwater and estuarine ecosystems.

2.3 HYDROLOGICAL SYMBOLS, CODES AND ACCURACY OF MEASUREMENTS

2.3.1 Units and symbols

Standardization of units and symbols is desirable and can be achieved through the use of those recommended in Tables I.2.2–I.2.4 (ISO, 1993). Commonly used units and conversion factors are also given. All symbols and units used in the Guide conform to those in the tables.

2.3.2 Hydrological codes

2.3.2.1 General

All systems for the transmission of data make use of some form of coding method, the purpose of which is to ensure that the information is transmitted quickly and reliably (9.3). In the case of fully automated systems, the information must be put into coded form before being processed. For these reasons, the codes are composed of standard forms that enable the information to be transmitted and given in a form compatible with processing. Such processing is usually preceded by quality control (9.8).

The structure of international codes is governed by convention, and codes are developed as a collective effort. For a long time, WMO has been developing codes to meet requirements for the exchange of meteorological data.

In operational hydrology, requirements for data are not on a worldwide scale and yet there have been a multiplicity of codes introduced in this field. This led the WMO Commission for Hydrology to develop international hydrological codes. The purpose of these codes is to cover general requirements so that, as far as possible, the procedures for coding and collecting hydrological data are standardized. The HYDRA and HYFOR codes, which were developed and used in the past, are no longer recommended for use. Instead, the character form for the representation and exchange of data (CREX) code has been developed in recent years for use in the representation and transmission of hydrometeorological data.

This code may be found to be particularly useful in the case of large national and international basins, in which a large number of stations are connected to a processing centre. The observations are coded, usually manually, by an observer, and then transmitted to a collecting centre for processing.

2.3.2.2 Character form for the representation and exchange of data

CREX is the name of a character code for the representation and exchange of meteorological, hydrological and water-quality data. Although originally designed for the exchange of data for which there were no suitable existing WMO code forms, CREX has been used recently as standard code form for data transmitted from data-collection platforms (DCPs). A CREX message shall consist of one or more subsets of related meteorological data defined, described and represented by a single CREX entity. For observational data, each subset shall correspond

Table I.2.2. Recommended symbols, units and conversion factors

I	*II*	*III*	*IV*	*V*	*VI*	*VII*
			Units			
Item	*Element*	*Symbol*	*Recommended*	*Also in use*	*Conversion factor**	*Remarks*
1	Acceleration due to gravity	*g*	m s^{-2}	ft s^{-2}	0.305	ISO
2	Albedo	*r*		Expressed as a decimal		
3	Area (cross-sectional) (drainage basin)	*A*	m^2	ft^2	0.0929	ISO
			km^2	acre ha $mile^2$	0.00405 0.01 2.59	ISO
4	Chemical quality		mg l^{-1}	ppm	~ 1	For dilute solutions
5	Chezy coefficient $[v\ (R_h S)^{-1/2}]$	*C*	$m^{1/2}\ s^{-1}$	$ft^{1/2}\ s^{-1}$	0.552	ISO
6	Conveyance	*K*	$m^3\ s^{-1}$	$ft^3\ s^{-1}$	0.0283	ISO
7	Degree day	*D*	Degree day	Degree day	Conversion formula: °C = 5/9 (°F–32)	Column IV is based on °C scale and column V on °F scale
8	Density	*p*	kg m^{-3}	lb ft^{-3}	16.0185	ISO
9	Depth, diameter, thickness	*d*	m cm	ft in	0.305 2.54	ISO
10	Discharge (river-flow) (wells)	*Q* Q_{we}	$m^3\ s^{-1}$ l s^{-1}	$ft^3\ s^{-1}$ gal (US) min^{-1}	0.0283 0.063	ISO
	(unit area–$Q\ A^{-1}$, or partial)	*q*	$m^3\ s^{-1}\ km^{-2}$ l $s^{-1}\ km^{-2}$	$ft^3\ s^{-1}\ mile^{-2}$	0.0109 10.9	ISO
11	Drawdown	*s*	m cm	ft	0.305 30.5	
12	Dynamic viscosity (absolute)	η	N s m^{-2}			ISO Pa, s, kg $m^{-1}\ s^{-1}$ also in use
13	Evaporation	*E*	mm	in	25.4	
14	Evapotranspiration	*ET*	mm	in	25.4	
15	Froude number	*Fr*		Dimensionless number		ISO
16	Head, elevation	*z*	m	ft	0.305	ISO
17	Head, pressure	h_p	m	kg (force) cm^{-2} lb (force) in^{-2}	10.00 0.705	
18	Head, static (water level) = $z + h_p$	*h*	cm	ft	30.05	ISO
		h	m		0.305	
19	Head, total = $z + h_p + h_v$	*H*	m	ft	0.305	ISO
20	Head, velocity = $v^2\ (2g)^{-1}$	h_v	cm m	ft	30.05 0.305	

(continued)

I	*II*	*III*	*IV*	*V*	*VI*	*VII*
Item	*Element*	*Symbol*	*Units*		*Conversion factor**	*Remarks*
			Recommended	*Also in use*		
21	Hydraulic conductivity (permeability)	*K*	cm s^{-1}	m d^{-1}	0.00116	
				ft min^{-1}	0.508	
22	Hydraulic diffusity = TC_s^{-1}	*D*	cm^2 s^{-1}			
23	Hydraulic radius = $A\,P_w^{-1}$	R_h	m	ft	0.305	ISO
24	Ice thickness	d_g	cm	in	2.54	
25	Infiltration	*f*	mm	in	25.4	
26	Infiltration rate	I_f	mm h_{-1}	in h_{-1}	25.4	
27	Intrinsic permeability	*k*	10^{-8} cm^2	Darcy	0.987	
28	Kinematic viscosity	*v*	m^2 s^{-1}	ft^2 s^{-1}	0.0929	ISO
29	Length	*l*	cm	in	2.54	ISO
			m	ft	0.305	
			km	mile	1.609	
30	Manning's coefficient = $R_h^{2/3}\,S^{1/2}\,v^{-1}$	*n*	s $m^{-1/3}$	s $ft^{-1/3}$	1.486	ISO l/n = k roughness coefficient can also be used
31	Mass	*m*	kg	lb	0.454	ISO
			g	oz	28.35	
32	Porosity	*n*	%			α may also be used if needed
33	Precipitation	*P*	mm	in	25.4	
34	Precipitation intensity	I_p	mm h^{-1}	in h^{-1}	25.4	
35	Pressure	*p*	Pa	hPa	100.0	See item 17
				mm Hg	133.3	
				in Hg	3386.0	
36	Radiation** (quantity of radiant energy per unit area)	*R*	J m^{-2}	ly	4.187 x 10^4	
37	Radiation intensity** (flux per unit area)	I_R	J m^{-2} s^{-1}	ly min^{-1}	697.6	
38	Radius of influence	r_2	m	ft	0.305	
39	Recession coefficient	C_r	Expressed as a decimal			

(continued)

I	*II*	*III*	*IV*	*V*	*VI*	*VII*
			Units			
Item	*Element*	*Symbol*	*Recommended*	*Also in use*	*Conversion factor**	*Remarks*
40	Relative humidity (moisture)	U	%			
41	Reynolds number	R_e		Dimensionless number		ISO
42	Runoff	R	mm	in	25.4	
43	Sediment concentration	c_s	kg m^{-3}	ppm	Depends on density	
44	Sediment discharge	Q_s	t d^{-1}	ton (US) d^{-1}	0.907	
45	Shear stress	τ	Pa			ISO
46	Slope (hydraulic, basin)	S		Dimensionless number		ISO
47	Snow cover	A_n	%			
48	Snow depth	d_n	cm	in	2.54	
49	Snow melt	M	mm	in	25.4	Normally expressed as daily
50	Soil moisture	U_s	% volume	% mass	Depends on density	
51	Soil moisture deficiency	U'_s	mm	in	25.4	
52	Specific capacity = $Q_{we}\ s^{-1}$	C_s	m^2 s^{-1}	ft^2 s^{-1}	0.0929	
53	Specific conductance	K	μS cm^{-1}			at θ = 25°C
54	Specific yield	Y_s		Expressed as a decimal		
55	Storage	S	m^3	ft^3	0.0283	
56	Storage coefficient (groundwater)	C_S		Expressed as a decimal		
57	Sunshine	n/N		Expressed as a decimal		Actual (n)/possible (N) hours
58	Surface tension	σ	N m^{-1}			ISO
59	Temperature	θ	°C	°F	Conversion formula °C = 5/9 (°F–32)	ISO *t* also in use
60	Total dissolved solids	m_d	mg l^{-1}	ppm	~ 1	For dilute solutions
61	Transmissivity	T	m^2 d^{-1}	ft^2 d^{-1}	0.0929	
62	Vapour pressure	e	Pa	hPa mm Hg	100.0 133.3 3386.0	
63	Velocity (water)	v	m s^{-1}	ft s^{-1}	0.305	ISO
64	Volume	V	m^3	ft^3 acre ft	0.0283 1230.0	ISO

(continued)

I	*II*	*III*	*IV*	*V*	*VI*	*VII*
Item	*Element*	*Symbol*	*Units*		*Conversion factor**	*Remarks*
			Recommended	*Also in use*		
65	Water equivalent of snow	w_n	mm	in	25.4	
66	Weber number	W_e	Dimensionless number			
67	Wetted perimeter	P_w	m	ft	0.305	
68	Width (cross-section, basin)	*b*	m km	ft mile	0.305 1.609	ISO
69	Wind speed	*u*	$m\ s^{-1}$	$km\ h^{-1}$ $mile\ h^{-1}$ k_n (or kt)	0.278 0.447 0.514	
70	Activity (amount of radioactivity)	*A*	Bq (Becquerel)	Ci (Curie)	3.7×10^{10}	IAEA
71	Radiation fluence (or energy fluence)	*F*	$J\ m^{-2}$	$erg\ cm^{-2}$	10^3	IAEA
72	Radiation flux intensity (or energy flux intensity)	*I*	$J\ m^{-2}\ s^{-1}$	$erg\ cm^{-2}\ s^{-1}$	10^3	IAEA

Note: Where international symbols exist, these have been used where appropriate and are indicated as ISO in the last column.
* Column IV = Conversion factor (Column VI) x Column V
** General terms. For detailed terminology and symbols, see the *Guide to Meteorological Instruments and Methods of Observation* (WMO-No. 8).

Table I.2.3. Miscellaneous symbols

Item	*Unit*	*Symbol*	*Remarks*
1	Concentration	*c*	ISO
2	Coefficient (in general)	*C*	ISO
3	Difference	Δ	ISO, values expressed in same units
4	Inflow	*I*	
5	Lag time	Δ*t*	various units
6	Load	*L*	
7	Number of (or rank)	*m*	ISO
8	Outflow	*O*	
9	Recharge	*f*	(See item 25 in Table I.2.2)
10	Total number	*N*	

Table I.2.4. Recommended units as appearing in Table I.2.2.

Item	*Unit*	*Symbol*	*Remarks*
1	Centimetre	*cm*	ISO
2	Day	*d*	ISO
3	Degree Celsius	˚C	ISO
4	Gram	*g*	ISO
5	Hectare	*ha*	
6	Hectopascal	*hPa*	ISO
7	Hour	*h*	ISO
8	Joule	*J*	ISO
9	Kilogramme	*kg*	ISO
10	Kilometre	*km*	ISO
11	Knot	*kn, kt*	
12	Litre	*l*	ISO
13	Metre	*m*	ISO
14	Microsiemens	μ*S*	
15	Milligram	*mg*	ISO
16	Millimetre	*mm*	ISO
17	Minute	*min*	ISO
18	Newton	*N*	ISO
19	Parts per million	*ppm*	
20	Pascal	*Pa*	ISO
21	Percentage	*%*	
22	Second	*s*	ISO
23	Tonne (metric ton)	*t*	ISO
24	Year	*a*	ISO
25	Bequerel	*Bq*	IAEA

to one report. CREX uses many of the principles of the previous BUFR code, and each message consists of sections as follows:

Section number	*Name*	*Contents*
0	Indicator section	CREX
1	Data description section	CREX master table number, edition number, table version number, data category, then a collection of descriptors which define the form and content of data subsets making the data section and an optional check digit indicator E
2	Data section	A set of data items defined by section 1
3	Optional section	SUPP followed by additional items for local use
4	End section	7777

Further information can be found at http://www.wmo.int/pages/prog/www/WMOCodes.html.

2.3.3 Accuracy of hydrological measurements

2.3.3.1 Basic principles

Theoretically, the true values of hydrological elements cannot be determined by measurements because errors of measurement cannot be eliminated completely. The uncertainty in measurement has a probabilistic character that can be defined as the interval in which the true value is expected to lie with a certain probability or confidence level. The width of the confidence interval is also called error band.

If measurements are independent one from the other, the uncertainty in the results of measurements can be estimated by taking at least

20–25 observations and calculating the resulting standard deviation, and then determining the confidence level of the results. This procedure cannot usually be followed in hydrometric measurements, because of the change in the value to be measured during the measuring period. For instance, many consecutive measurements of discharge with current meters at constant stage is clearly impracticable in field conditions. Thus an estimate of the uncertainty has to be made by examining the various sources of errors in the measurement.

Another problem in applying statistics to hydrological data arises from the assumption that observations are independent random variables from a fixed statistical distribution. This condition is seldom met in hydrological measurements. River flow is, by nature, not purely random. It depends on previous values. It is generally accepted that some aspects of the departure of hydrological data from the theoretical concept of errors is not serious. However, it should be stressed that no statistical analysis can replace correct observations, in particular because spurious and systematic errors cannot be eliminated by such analysis. Only random errors can be characterized by statistical means.

Section 2.3.3 contains definitions of basic terms related to the accuracy of hydrological measurements. Methods for estimating uncertainty are introduced and numerical values of accuracy, required for the most important hydrological parameters, are given. References to the existing recommendations contained in the *Technical Regulations* (WMO-No. 49) and other publications are also included.

2.3.3.2 Definitions of terms related to accuracy

The definitions of the terms related to accuracy given below take into account those given in the *Technical Regulations* (WMO-No. 49), Volume III – Hydrology and in the *Guide to Meteorological Instruments and Methods of Observation* (WMO-No. 8):

Accuracy: The extent to which a measurement agrees with the true value. This assumes that all known corrections have been applied.

Confidence interval: The interval which includes the true value with a prescribed probability and is estimated as a function of the statistics of the sample (Figures I.2.3 and I.2.4).

Confidence level: The probability that the confidence interval includes the true value (Figures I.2.3 and I.2.4).

Correction: The value to be added to the result of a measurement to allow for any known systematic error and thus obtain a closer approximation to the true value.

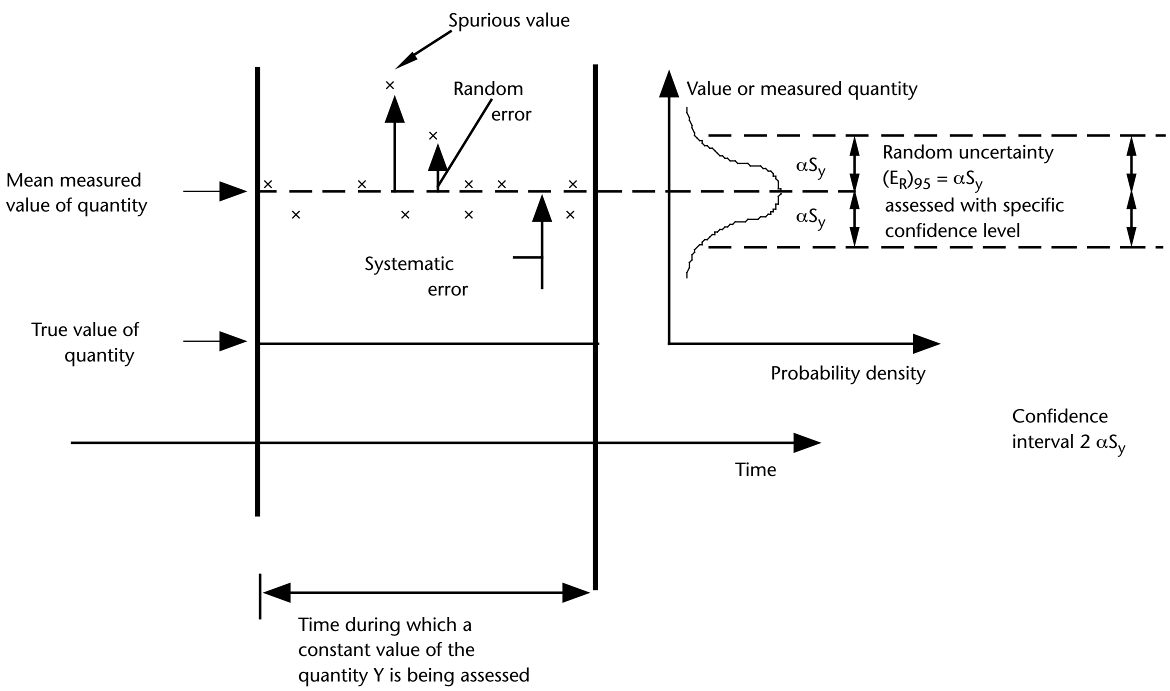


Figure I.2.3. Explanation of errors

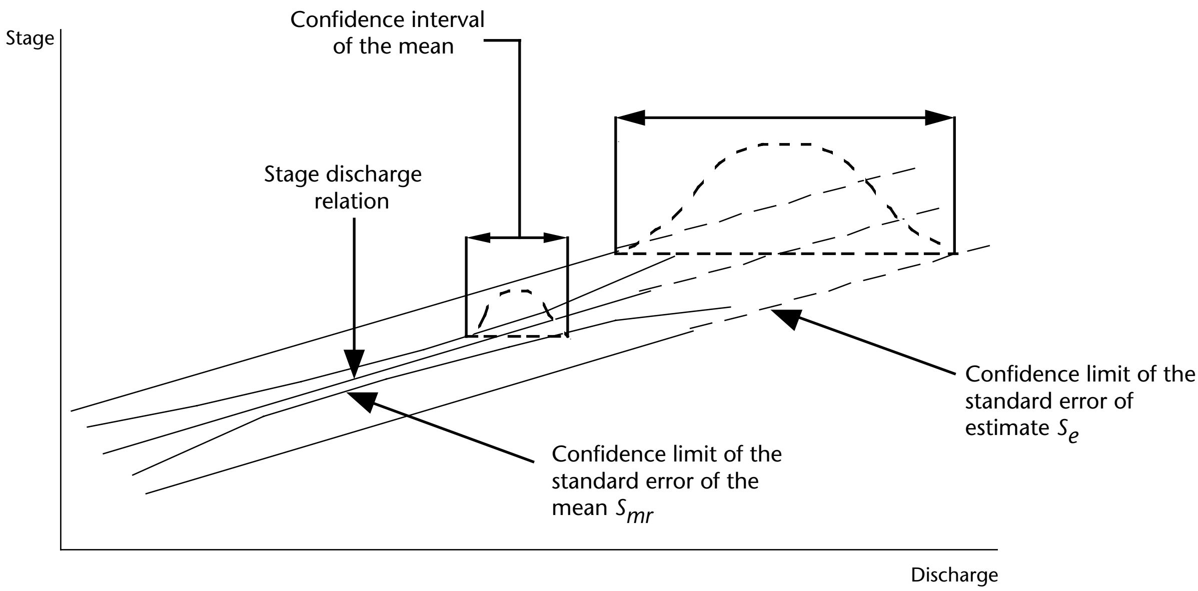


Figure I.2.4. Explanation of errors in linear regression

Error: The difference between the result of a measurement and the true value of the quantity measured. This term is also used for the difference between the result of a measurement and the best approximation of the true value, rather than the true value itself. The best approximation may be a mean of several or many measurements.

Expected value: The best approximation of the true value, which may be a mean of several, or of many measurements.

Hysteresis (instrument): That property of an instrument whereby it gives different measures, for the same actual value, according to whether that value has been reached by a continuously increasing or continuously decreasing change of the variable.

Measurement: An action intended to assign a number as the value of a physical quantity in stated units. The result of a measurement is complete if it includes an estimate (necessarily in statistical terms) of the probable magnitude of the uncertainty.

Normal distribution: A mathematically defined, symmetrical, bell-shaped, continuous distribution, traditionally assumed to represent random errors.

Precision: The closeness of agreement between independent measurements of a single quantity obtained by applying a stated measurement procedure several times under prescribed conditions. Accuracy has to do with closeness to the truth, precision has to do only with closeness together. Precision of observation or of reading is the smallest unit of division on a scale of measurement to which a reading is possible either directly or by estimation.

Random error: That part of the error that varies in an unpredictable manner, in magnitude and in sign, when measurements of the same variable are made under the same conditions (Figure I.2.3).

Range: The interval between the minimum and maximum values of the quantity to be measured, for which the instrument has been constructed, adjusted or set. It can be expressed as a ratio of maximum and minimum measurable values.

Reference measurement: A measurement utilizing the most advanced state of science and the latest technologies. The result of the reference measurement is used to estimate a best approximation to the true value.

Repeatability: The closeness of agreement, when random errors are present, between measurements of the same value of a quantity obtained under the same conditions, that is, the same observer, the same instrument, the same location, and after intervals of time short enough for real differences to be insignificant.

Reproducibility: The closeness of agreement between measurements of the same value of a quantity obtained under different conditions, for example, different observers, instruments, locations, and after intervals of time long enough for erroneous differences to be insignificant.

Resolution: The smallest change in a physical variable that causes a variation in the response of a measuring system.

Sensitivity: The relationship of the change of the response to the corresponding change of the stimulus, or the value of the stimulus required to produce a response exceeding, by a specified amount, the response already present due to other causes.

Spurious value: Value known for certain to be in error, for example, due to human mistakes or instrument malfunction (Figure I.2.3).

Standard deviation (S_y): This is a measure of the dispersion of values about their mean. It is defined as the positive square root of the sum of the squares of the deviation from the arithmetic mean, divided by (n – 1). It is given by:

$$S_y = \left[\frac{\sum_{1}^{n} (y_i - \overline{y})^2}{n - 1} \right]^{1/2} \tag{2.3}$$

where $\overline{y}$ is the arithmetic mean of the sample of n independent measurement of the variable y, and (n – 1) indicates the loss of one degree of freedom.

Standard error of estimate (S_e): A measure of the variation or scatter of the observations about a linear regression. It is numerically similar to the standard deviation except that the linear-regression relation replaces the arithmetic mean and (n – 1) is replaced by (n – m):

$$S_e = \left[\frac{\sum (d)^2}{n - m} \right]^{1/2} \tag{2.4}$$

where d is the deviation of an observation from the computed regression value, m is the number of constants in the regression equation, and (n – m) represent the degrees of freedom in the equation derivation.

Systematic error: That part of the error that either:

(a) Remains constant in the course of a number of measurements of the same value of a given quantity; or
(b) Varies according to a definite law when conditions change (Figure I.2.3).

Tolerance: The permissible accuracy in the measurement of a specified variable.

Tolerance limit: The limiting lower or upper value specified for a quantitative characteristic.

True value: The value that characterizes a quantity in the conditions that exist at the moment when that quantity is observed. It is an ideal value that could be known only if all causes of error were eliminated.

Uncertainty: The interval about the measurement within which the true value of a quantity can be expected to lie with a stated probability (Figure I.2.3). The numerical value of uncertainty is a product of the true standard deviation of the errors and a numerical parameter depending on the confidence level:

$$e = \pm \alpha\sigma_y \approx \alpha s_y \tag{2.5}$$

The standard deviation, s_y, computed from n observations, approaches the true standard deviation, σ_y, as n approaches infinity. In the case of normal distribution of error, numerical parameters are as follows:

Confidence level	α
0.50	0.674
0.60	0.842
0.66	0.954
0.80	1.282
0.90	1.645
0.95	1.960
0.98	2.326
0.99	2.576
0.999	3.291

2.3.3.3 Types of error

Spurious errors should be eliminated by discarding the values of measurements concerned.

These errors can be identified by a statistical-outlier test, such as the one described in ISO 5168 (ISO, 2005) that gives a rejection criterion.

Systematic error originates mainly from instrumentation and cannot be reduced by increasing the number of measurements, if the instruments and conditions remain unchanged. If the systematic error has a known value, this value should be added to or subtracted from the result of the measurement, and error due to this source should be considered zero. Systematic error should be eliminated by correcting, properly adjusting or changing the instrument, and/or by changing the flow conditions, for example, the length of straight approach channel of a stream-gauging section. These errors are often due to difficult measuring conditions, such as unsteady flow, meandering and bad location of stations.

Random errors cannot be eliminated, but their effects can be reduced by repeated measurements of the element. The uncertainty of the arithmetic mean computed from n independent measurements is several times smaller than the uncertainty of a single measurement. The distribution of random errors can usually be assumed to be normal (Gaussian). For certain cases, normal distribution can or should be replaced by other statistical distributions.

2.3.3.4 Sources of error

Each instrument and measuring method has its own sources of error. Therefore, it would be difficult to list all possible sources of error. The specific sources are usually mentioned in the descriptions of the design of the instruments and operating procedures, such as those in ISO Standards, and the *Manual on Stream Gauging* (WMO-No. 519). Some typical sources of error include:

(a) Datum or zero error originates from the incorrect determination of the reference point of an instrument, for example, staff-gauge zero level, difference between the staff-gauge zero and the weir-crest levels;
(b) Reading error results from the incorrect reading of the indication by the measuring instrument, for example, due to bad visibility, waves, or ice at the staff gauge;
(c) Interpolation error is due to inexact evaluation of the position of the index with reference to the two adjoining scale marks between which the index is located;
(d) Observation error is similar to the reading error and is attributed to neglect or incompetence of the observer;
(e) Error due to the negligence of one or several variables needed to determine the measured value (for example, assuming a unique stage-discharge relationship during periods of unsteady flow when slope as well as stage is a significant determinant of discharge);
(f) Hysteresis (definition under 2.3.3.2);
(g) Non-linearity error is that part of error whereby a change of indication or response departs from proportionality to the corresponding change of the value of the measured quantity over a defined range;
(h) Insensitivity error arises when the instrument cannot sense the given change in the measured element;
(i) Drift error is due to the property of the instrument in which its measurement properties change with time under defined conditions of use, for example, mechanical clockworks drift with time or temperature;
(j) Instability error results from the inability of an instrument to maintain certain specified metrological properties constant;
(k) Out-of-range error is due to the use of an instrument beyond its effective measuring range, lower than the minimum or higher than the maximum value of the quantity, for which the instrument/installation has been constructed, adjusted, or set (for example, unexpected high water level);
(l) Out-of-accuracy class error is due to the improper use of an instrument when the minimum error is more than the tolerance for the measurement.

2.3.3.5 Secondary errors of measurement

Hydrological observations are often computed from several measured components. For example, discharge at measuring structures is computed as a function of a discharge coefficient, characteristic dimensions and head. For estimating the resultant uncertainty, the Gauss error transfer (propagation) theory can be applied.

Resultant uncertainty is often referred to as overall uncertainty, which can be calculated from the uncertainties of the individual components if the errors of the individual components are assumed to be statistically independent.

If a quantity, Q, is a function of several measured quantities, x, y and z, the resultant uncertainty, e_Q, in Q due to uncertainties, e_x, e_y and e_z, in x, y and z, respectively, should be evaluated by the simplified equation of the transfer (propagation):

$$(e_Q)^2 = \left(\frac{\partial_Q}{\partial x} e_x\right)^2 + \left(\frac{\partial_Q}{\partial y} e_y\right)^2 + \left(\frac{\partial_Q}{\partial z}\right)^2 \quad (2.6)$$

where ∂_Q/∂_x, ∂_Q/∂_y and ∂_Q/∂_z are the partial differentials of the function expressing explicitly the relationship of the dependent variable with the independent variables.

In hydrological measurements, it is very rare that a measurement can be repeated under the same conditions in the field. The standard deviation should therefore be determined by using data of changing variables as in the case of a discharge rating curve.

The standard error of estimate:

$$s_e = \left(\frac{\sum d^2}{n-2} \right)^{1/2} \quad (2.7)$$

of the mean of observations is extremely important for characterizing the stage-discharge relationship, which needs special treatment because the relationship is not linear, but approximately logarithmic. It is an estimate of the accuracy of the computed mean relationship in a regression and, therefore, it is the range within which the true mean would be expected to lie (Figure I.2.4).

For small samples, it could be useful to have a corrected standard error of estimate, obtained by multiplying s_e by $\left(\frac{n}{n-2}\right)^{1/2}$, resulting as:

$$s_{mr} = \frac{s_e}{\sqrt{n}} \quad (2.8)$$

2.3.3.6 Characterization of instruments and methods of observation

The accuracy of a measuring instrument can be characterized by an uncertainty at a given value, corresponding to a maximum or minimum measurable value. The accuracy of an instrument without a reference value can be misunderstood or misinterpreted. The instrument accuracy is in many cases only one component of the overall accuracy of the measurement.

For characterization of uncertainty, the 95 per cent confidence level is commonly used. That is, in 5 per cent of the cases, the error could be outside the stated confidence interval. According to the *Technical Regulations* (WMO-No. 49), Volume III, measurement uncertainties should be reported in one of the following forms:

(a) Uncertainties expressed in absolute terms: Measured value of hydrological elements, for example, discharge: Q = ...
Random uncertainty: $(e_r)_{95}$ = ...

(b) Uncertainties expressed in percentage terms: Measured value of the hydrological elements Q = ...
Random percentage uncertainty $(e_r)_{95\%}$= ...%

In practice, uncertainties of measurements are given in a form where uncertainty is expressed as a ratio (or percentage) of Q_m, the measured value. For example, in the case of $(e_r)_{95}$ = 10%, $Q_m \pm 0.10\ Q_m$ will contain the true value of Q 95 per cent of the time. In this case, the uncertainty is formulated by assuming average measurement conditions.

2.3.3.7 Recommended accuracy of hydrological measurements

The recommended accuracy depends mainly on the anticipated use of the measured data (the purpose of the measurement), on the potentially available instruments and on the available financial resources. Therefore, it cannot be a constant value. Rather it should be a flexible range. The recommended accuracy levels are tabulated in Table I.2.5 as a general guidance for instruments and methods of observation. In many countries, national standards regulate the required accuracies.

2.3.4 Calibration of instruments

One of the major sources of error, as stated above, is due to change in measurement characteristics of the instruments. Hydrological instrumentation comprises a large variety of mechanical, electromechanical and electronic devices. Mechanical instruments such as current meters or anemometers provided by reputable manufacturers are made with precision dies and are usually supplied with a factory calibration table. The factory calibration will, of course, only apply if the instrument is not damaged in use and is properly maintained. Many national hydrological agencies operate facilities to verify factory calibrations and international standards for the manufacture and calibration of, for example, current meters.

Increasingly, there is a trend towards replacing mechanical devices with electronic ones. Although they are more reliable than mechanical devices, they usually are not repairable in the field and must simply be substituted for a replacement device. Electronic instrumentation poses particular problems for hydrological agencies that may be making a transition from electromechanical devices to electronic ones as the calibration issues may be quite different. Calibration of an electronic instrument may drift due to temperature or pressure changes, or solid-state sensors may become fouled during use. It is essential that instruments be designed to function in the range of conditions that are likely to occur at the data-collection site. Some instruments have built-in calibration checks and it is important that these be used.

Table I.2.5. Recommended accuracy (uncertainty levels) expressed at the 95 per cent confidence interval

Precipitation (amount and form)	3–7%
Rainfall intensity	1 mm h^{-1}
Snow depth (point)	1 cm below 20 cm or 10% above 20 cm
Water content of snow	2.5–10%
Evaporation (point)	2–5%, 0.5 mm
Wind speed	0.5 m s^{-1}
Water level	10–20 min
Wave height	10%
Water depth	0.1 m, 2%
Width of water surface	0.5%
Velocity of flow	2–5%
Discharge	5%
Suspended sediment concentration	10%
Suspended sediment transport	10%
Bed-load transport	25%
Water temperature	0.1–0.5°C
Dissolved oxygen (water temperature is more than 10°C)	3%
Turbidity	5–10%
Colour	5%
pH	0.05–0.1 pH unit
Electrical conductivity	5%
Ice thickness	1–2 cm, 5%
Ice coverage	5% for ≥ 20 kg m^{-3}
Soil moisture	1 kg m^{-3} ≥ 20 kg m^{-3}

Notes:

1. When a range of accuracy levels is recommended, the lower value is applicable to measurements under relatively good conditions and the higher value is applicable to measurements under difficult situations.
2. Obtaining the recommended accuracy of precipitation measurements, 3–7 per cent, will depend on many factors, including gauge characteristics. For gauges having their orifice above the ground, the gauge catch deficiency is strongly determined by wind speed and precipitation type. The catch deficiency for light snow falling during strong wind can for example be 50 per cent or more.

2.4 DESIGN AND EVALUATION OF HYDROLOGICAL NETWORKS

2.4.1 General concepts of network design

A hydrological data network is a group of data-collection activities that is designed and operated to address a single objective or a set of compatible objectives. Frequently, the objectives are associated with a particular use that is anticipated for the data being collected in the network – for example, for a water resources assessment, a development plan, or a project design. A particular hydrological station or gauge may be included in more than one network if its data are being used for more than one purpose. In most parts of the world this is more commonly the case than not. Alternatively, a single network may consist of several types of station or gauge if they are all contributing information to the network's objective. For example, both raingauges and stream gauges might be included in a flood forecasting network.

The term network is frequently used in a less rigorous sense. It is often possible to hear of surface-water network, groundwater network, precipitation network, or water-quality network when the speaker is referring to an aggregation of gauges and stations that have no coherence in their objectives. Data-collection sites included in a network under this looser definition may even have disparate uses for the data being collected. This disparity of usage is more than just a semantical oddity. It can cause confusion and false expectations when network analysis and design are being discussed among programme managers and hydrologists.

A network design could be based on a maximization of the economic worth of the data that are to be collected. However, such is not the case in the real world. Generally, in water resources decision-making, the economic impacts of hydrological data are never considered. Decisions are made based on the available data; the option of delaying the decision to collect more data is not explored, or deemed unacceptable. However, several examples of exceptions to this general rule are contained in the *Cost–benefit Assessment Techniques and User Requirements for Hydrological Data* (WMO-No. 717) and in the *Proceedings of the Technical Conference on the Economic and Social Benefits of Meteorological and Hydrological Services* (WMO-No. 733). A review of the hydrometric network in one Canadian province indicated that the cost–benefit ratio of the existing provincial network was 19 and that the network could be tripled in size to maximize economic benefits (Azar and others, 2003). Even in nations with very dense hydrometric networks, such as the United Kingdom, economic analysis inevitably demonstrates that benefits of hydrometric networks exceed the cost (CNS, 1991). Nonetheless many countries suffered considerable reductions in their hydrological networks in the 1980s and 1990s as a consequence of budget reductions for monitoring agencies (Pearson, 1998). For example, network reductions in Canada, Finland, New Zealand and the United States of America were 21, 7, 20 and 6 per cent, respectively. Network reductions, with rare exceptions such as New Zealand, continue.

In lieu of complete economic analyses, network designs are usually based on surrogate measures of the economics or on guidance such as that presented subsequently in this chapter.

2.4.1.1 Definition of network design

A complete network design answers the following questions pertaining to the collection of hydrological data:

(a) What hydrological variables need to be observed?
(b) Where do they need to be observed?
(c) How often do they need to be observed?
(d) What is the duration of the observation programme?
(e) How accurate should the observations be?

To answer these questions, network design can be conceptualized as a pyramid, as shown in Figure I.2.5. The base of the pyramid is the science of hydrology. Without a thorough understanding of the hydrological setting of the area in which the network is to be established, there is little chance that the resulting network will generate information in an effective manner. Hydrological understanding comes from both education and experience, but there is no substitute for experience when initiating a hydrological network in an area where little or no historical data are available.

The right-hand side of the pyramid deals with quantitative methods for coping with hydrological uncertainty. Because of measurement errors and errors caused by sampling in space and time, there will always be hydrological uncertainty. Perfect hydrological information can never exist. Probabilistic descriptions of these errors are the most effective means of dealing with the resulting uncertainty. Probability theory provides the theorems and the language for doing so and also yields the understanding that is necessary for appropriate use of the tools of statistics. In Figure I.2.5, statistical tools are represented by sampling theory and by correlation and regression analyses, which are commonly used in quantitative network-design approaches. However, there are many other branches of statistics that may be found useful in network analysis and design. The capstone of uncertainty is Bayesian analysis, which pertains to the level of uncertainty in the descriptions of

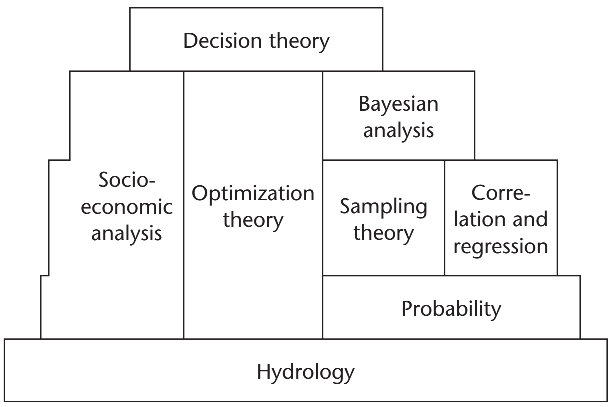


Figure I.2.5. The basic building blocks of network design

hydrological uncertainty. In other words, the probabilistic descriptions of uncertainty, based on statistics of finite samples of hydrological data, are uncertain in themselves. Reduction of uncertainty about uncertainty is a key aspect of taking full advantage of the information contained in the data that the network will generate.

The column in the middle of the structure, labelled optimization theory, is often included taxonomically as a part of socio-economic analysis. However, even in the absence of socio-economics, the optimization theory is often used in hydrological network design. Thus, it is included here as a separate component of the structure. A suite of mathematical programmes, each with its own utility and shortcomings, comprises optimization theory, which is often referred to as operations research. The context of the network-design problem determines which, if any, of the mathematical programmes can be used in a given situation. Often, the choice between two or more network designs must be made on the basis of judgement because appropriate optimization tools either do not exist or are too consuming of computer resources to be efficient.

Atop the pyramid is decision theory, which is a formal mechanism for integrating all of the underlying components. The application of decision theory in network design is not required – it is not even possible in most circumstances. However, an understanding of its pretexts and premises can make a network designer more cognizant of the impacts of his or her final decisions.

The left-hand side of the pyramid represents a rather amorphous group of technologies under the heading of socio-economic analysis. In addition to social sciences and economics, this part of the network-design structure also encompasses policy science and even politics. The latter plays a very important role in the realization of the potential benefits of water and, thus, also in the ultimate value of the data from the network. The left-hand side of the structure is the part that usually receives little rigorous consideration in the design of the data network. This is probably attributable to two causes: the subject matter is difficult to treat in an objective, mathematical way; and to do so in a substantive manner requires the synthesis of inputs from many disciplines beyond those of hydrology and water resources engineering. Thus, a network design that includes a significant socio-economic analysis will probably be both expensive and time-consuming.

Nevertheless, hydrological data-collection sites are often installed to meet pressing social needs and economic constraints with relatively little thought to meeting long-term hydrological information needs. Aside from meeting scientific needs, data-collection sites may be installed to assist water mangers in responding to extreme events such as floods or droughts, allocating water supplies among competing uses, or meeting regulatory requirements. Sites operated for these latter purposes may also lead to increased hydrological understanding, but the resulting network is by no means optimized for that purpose.

2.4.1.2 Surrogate approaches

Since full-scale and complete network design is either impossible or impractical in today's world, approaches that substitute surrogate measures, objectives, or criteria are actually used to answer the questions that comprise network design. For example, a common substitution is to maximize information content from a network in lieu of optimizing the economic value of the data. Studies have shown that, if information is used properly, it can be expected to contribute to the economic worth resulting from a decision. The more information, the better the decision. However, the economic impact of information is not linearly related to its magnitude and the marginal worth of additional information decreases with the amount of information that is available. Thus, the use of this surrogate criterion can lead a Hydrological Service in the right direction if only sparse hydrological information is available, but its use can cause the collection of excess data if the region of interest already has a reasonably adequate information base.

Among the basic analytical techniques that take advantage of surrogates in the design of networks are cartographic analysis, correlation and regression methods, probabilistic modelling, deterministic modelling and regionalization techniques. Each method has particular applications and the choice depends on the limitations of available data and the type of problem under consideration. Quite often the different techniques are combined in certain applications. The *Casebook on Hydrological Network Design Practice* (WMO-No. 324) presents applications of these techniques as a means of determining network requirements. Further examples are contained in other publications (WMO/IHD Project Report No. 12; WMO-Nos. 433, 580, 806).

2.4.1.3 The basic network

The worth of the data that derive from a network is a function of the subsequent uses that are made of them. Nevertheless, many of the uses of hydrological data are not apparent at the time of the network design and, therefore, cannot be used to justify the collection of specific data that ultimately may be of great value. In fact, few hydrological data would be collected if a priori economic justifications were required. However, modern societies have developed a sense that information is a commodity that, like insurance, should be purchased for protection against an uncertain future. Such an investment in the case of hydrological data is the basic network, which is established to provide hydrological information for unanticipated future water resources decisions. The basic network should provide a level of hydrological information at any location within its region of applicability that would preclude any gross mistakes in water resources decision-making. To accomplish this aim, at least three criteria must be fulfilled:

(a) A mechanism must be available to transfer the hydrological information from the sites at which the data are collected to any other site in the area;
(b) A means for estimating the amount of hydrological information (or, conversely, uncertainty) at any site must also exist;
(c) The suite of decisions must include the option of collecting more data before the final decision is made.

2.4.1.3.1 *The minimum network*

In the early stages of development of a hydrological network, the first step should be the establishment of a minimum network. Such a network should be composed of the minimum number of stations which the collective experience of hydrological agencies of many countries has indicated to be necessary to initiate planning for the economic development of the water resources.

The minimum network is one that will avoid serious deficiencies in developing and managing water resources on a scale commensurate with the overall level of economic development of the country. It should be developed as rapidly as possible by incorporating existing stations as appropriate. In other words, this pragmatic network will provide the basic framework for network expansion to meet future needs for specific purposes. It is emphasized that a minimum network will not be adequate for the formulation of detailed development plans and will not meet the numerous requirements of a developed region for the operation of projects and the management of water resources.

2.4.1.3.2 *Expanding the information base*

Once the minimum network is operational, regionalized hydrological relationships, interpreted information and models can be formulated for estimating general hydrological characteristics, including rainfall and runoff at any location in the area. The basic network of observing stations should be adjusted over time until regional hydrological relationships can be developed for ungauged areas that provide the appropriate level of information. In most cases, this adjustment will result in increases in the densities of hydrological stations. However, this is not always the case. Since models are used to transfer the information from the gauged to the ungauged sites, the quality of the model is also a factor in determining the density of the basic network. If a model is particularly good, it can distil the information from the existing data better than a poorer model, and the better model would require less data to attain a given level of regional information than would the poorer one. In an extreme situation, the regional model might be so good that the level of data collection in the basic network could be reduced.

Owing to the broad dependence on the stations in the basic network, it is very important that the records from all of these stations be of high quality. Even if the installation of a station is adequate, its records may be of little value if it is not operated correctly. Continuous operation may be difficult – especially over a period of 20 years or more. A minimum network, in which stations are abandoned or irregularly observed, will have its effective density reduced and is, therefore, no longer an adequate minimum network. For that reason, care should be taken not only in establishing, but also in providing for, the continuing operation of these stations and for monitoring the reliability and accuracy of the collected records.

Economic as well as technical considerations are involved in the design and implementation of basic networks, and the number of stations requiring observation over an indefinitely long period cannot be excessive. Consequently, a sampling procedure may be adopted to maximize the cost-effectiveness of the basic network. One such approach categorizes the stations as either principal or base stations, or secondary stations. The secondary stations are operated only long enough to establish a stable relationship, usually by means of correlations, with one or more of the base stations. A new secondary station can then be established with the equipment and funds that had been in use at the discontinued site. Records can be reconstructed at the discontinued site by means of the base-station records and the inter-station relationship. At times, it may be necessary to re-establish secondary stations if it is believed that the conditions either at the secondary site or at its related base station(s) have changed. The perpetual nature of the principal stations in the basic network provides a basis for monitoring long-term trends in hydrological conditions in the region. This is particularly important in the light of potential changes in the hydrological cycle that could be caused by land-use changes or by increases in stratospheric greenhouse gases.

2.4.1.4 Integrated network design

The hydrological cycle is a continuum, and its interconnections permit the partial transfer of information obtained in one part of the cycle to another. The efficiency of such transfers is proportional to the degree of hydrological understanding that is captured in the models that are used to route the water (and the information) between the parts of the cycle. For example, precipitation records on or near a gauged drainage basin permit the reconstruction of streamflow records during periods when the stream-gauge malfunctions if a valid precipitation-runoff model has been calibrated during times when all gauges were functioning properly. A groundwater observation well may perform a similar role for malfunctions of the stream gauge if the well is monitoring the water table of an aquifer that is directly connected to the stream.

To date, little has been done to include these interactions in network designs in an explicit manner. Ideally, the complementarity between the rain-gauges and the stream gauges that are operated in a flood-forecasting network could be used in designing a network for water resources assessment, for example. If the economic trade-offs between the two networks could be defined, they could be optimized together and peak efficiencies in information generation could be attained for both. In spite of this technological shortcoming, networks should be designed iteratively, and the outcomes of an existing design should become starting points for subsequent designs. By extension of the above example, this can be illustrated. The flood-forecasting network will probably have stream gauges and precipitation gauges at rather specific locations to meet its information needs. As the water resources assessment will generally have less specific requirements for its information sources, it will be likely that many of the gauges of the flood-forecasting network can be incorporated into the assessment network and used as initial given conditions for its design. This iterative approach is particularly useful when designing generalized networks, like the basic network on the basis of networks, with more restrictive information demands. Networks with more restrictive demands include benchmark stations, representative basins and networks for operational purposes.

2.4.1.4.1 *Stations for operational purposes*

Stations may be established for such specific purposes as reservoir operation, irrigation, navigation, water-quality monitoring or flood forecasting. Benchmark or reference stations would also belong to this category. The length of operation of special stations is related to the purpose for which they were installed.

In some cases, the specific purpose to be served may require observations on only one particular aspect of an element, or be confined to one season of the year. For example, a hydrometric station may consist of a crest gauge for recording only the maximum flood peak or a storage gauge for measuring the total precipitation during a season. Although such stations may perform a valuable function, they do not provide the data required for general hydrological analyses. Consequently, such stations may or may not be included in a basic hydrological network.

2.4.1.4.2 *Benchmark stations*

Each country and each natural region of large countries should contain one benchmark station to provide a continuing series of consistent observations on hydrological and related climatological variables. Hydrological benchmark stations should be established in areas that are relatively uninfluenced by past or future anthropogenic changes. Since long records are the essence of a benchmark station, consideration should be given to existing stations if they meet the other requirements. The Reference Hydrometric Basin Network of Canada is one such example (Harvey and others, 1999). Climatological benchmark stations are known as reference stations.

2.4.1.4.3 *Representative basins*

A representative basin is desirable in each natural region – especially in those regions where great economic growth is expected or where the hydrological problems are particularly difficult. In their simplest form, they permit the simultaneous study of precipitation and runoff, thus helping to make up for deficiencies in short periods of observation and low densities of minimum networks.

2.4.1.4.4 *Project stations*

These are stations established for a limited span of time, for specific purposes, often research oriented. Other frequent objectives may be investigations before or after physical interventions in the catchment, or for supplementing the regional coverage of the basic network. Project stations are characterized by:
(a) Limited lifetime;
(b) Data quality depending on purpose.

2.4.1.5 Conducting a network analysis

Figure I.2.6 lays out the steps that should be taken in conducting a review and redesign of an existing hydrological network. Such reviews should be conducted periodically to take advantage of the reduction in hydrological uncertainty brought about by the added data since the last network analysis and to tune the network to any changes in the socio-economic environment that may have transpired. The steps of the analysis are discussed individually below.

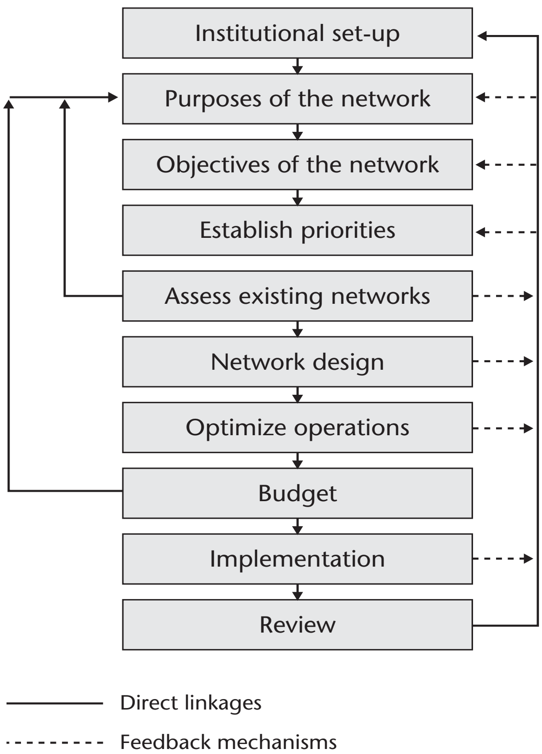


Figure I.2.6. A framework for network analysis and redesign

Institutional set-up

The roles and aims of all of the organizations involved in various aspects of water resources management should be defined and identified, particularly legislative responsibilities. Communication links between these organizations should be improved to ensure coordination and integration of data-collection networks.

Purposes of the network

The purposes of the network in terms of the users and uses of the data should be identified. Data users and uses can vary temporally and spatially. There is also a need to identify potential future needs and incorporate these into the design as well.

Objectives of the network

Based on the purpose of the network, an objective or set of objectives can be established in terms of the information required. An indication of the consequences of not being able to provide this information may prove useful later.

Establish priorities

If there is more than one objective, priorities need to be set for later evaluation. If all objectives can be met within the budget, then this is not needed. However, if they cannot be met, then the lower-priority objectives may not be met fully.

Assess existing networks

Information on the existing networks should be compiled and interpreted to determine if the current networks fulfil the objectives. This may include comparisons with other basins and/or networks.

Network design

Depending on the available information and the objectives defined, the most appropriate network-design technique or techniques should be applied. This may be simple hydrological characteristics, regression relationships, or more complex network analysis using generalized least squares methods.

Optimize operations

Operational procedures account for a significant portion of the cost of data collection. This includes the types of instrument, frequency of station visits and structure of field trips. The minimum-cost operational procedures should be adopted.

Budget

Based on the identified network and operational procedures, the cost of the operation of the network can be established. If this is within the budget, the next step can be followed. If not, either additional funding must be obtained or the objectives and/or priorities need to be examined to determine where costs may be reduced. The process adopted should allow the designer to express the impact of insufficient funding in terms of not meeting objectives or reduced information and net impacts.

Implementation

The redesigned network needs to be implemented in a planned manner. This will include both short- and long-term planning horizons.

Review

Since a number of the above components are variable in time, a review can be required at the instigation of any particular component – for example, changes in users or uses, or changes in the budget. To be ready to meet such changes, a continuous review process is essential.

2.4.2 Density of stations for a network

The concept of network density is intended to serve as a general guideline if specific guidance is lacking. As such, the design densities must be adjusted to reflect actual socio-economic and physio-climatic conditions. Computer-based mathematical analysis techniques should also be applied, where data are available, to optimize the network density required to satisfy specific needs.

As stated in 2.4.1.3.1, the minimum network is one that will avoid serious deficiencies in developing and managing water resources on a scale commensurate with the overall level of economic development and environmental needs of the country. It should be developed as rapidly as possible, incorporating existing stations, as appropriate. In other words, such a network will provide the framework for expansion to meet the information needs of specific water uses.

In the following sections, minimum densities of various types of hydrological stations are recommended for different climatic and geographic zones. These recommendations are based on the 1991 review of Members' responses regarding the WMO basic network assessment project (WMO/TD-No. 671) and are presented in Table I.2.6. However, these recommended network densities are being revisited through a study undertaken by the Commission for Hydrology and the revised recommended densities will be placed on the Website as part of the electronic version of the Guide.

It is impossible to define a sufficient number of zones to represent the complete variety of hydrological conditions. The simplest and most precise criterion for the classification of zones would be on the basis of the areal and seasonal variation of rainfall. Each country could present a good map of annual precipitation and a minimum network could be developed from this. However, this would

Table I.2.6. Recommended minimum densities of stations (area in km^2 per station)

Physiographic unit	*Precipitation*		*Evaporation*	*Streamflow*	*Sediments*	*Water quality*
	Non-recording	*Recording*				
Coastal	900	9 000	50 000	2 750	18 300	55 000
Mountains	250	2 500	50 000	1 000	6 700	20 000
Interior plains	575	5 750	5 000	1 875	12 500	37 500
Hilly/undulating	575	5 750	50 000	1 875	12 500	47 500
Small islands	25	250	50 000	300	2 000	6 000
Urban areas	–	10–20	–	–	–	–
Polar/arid	10 000	100 000	100 000	20 000	200 000	200 000

not help countries that need a network most as they have very few prior records, and the establishment of a good precipitation map is not possible. Also, the countries with very irregular rainfall distribution need to be considered as a special category. In such cases, it is not advisable to base the classification on this one characteristic.

Population density also affects network design. It is almost impossible to install and operate, in a satisfactory manner, a number of stations where population is sparse unless the stations are highly automated. Sparsely settled zones, in general, coincide with various climatic extremes, such as arid regions, polar regions or tropical forests.

At the other extreme, densely-populated urban areas need a very dense raingauge network for both temporal and spatial resolution of storms and for design, management and real-time control of the storm-drainage systems and for other engineering applications.

From these considerations, a limited number of larger zones have been defined for the definition of density norms in a somewhat arbitrary manner adopting some general rules. Six types of physiographic regions have been defined for minimum networks:
(a) Coastal;
(b) Mountainous;
(c) Interior plains;
(d) Hilly/undulating;
(e) Small islands (surface areas less than 500 km^2);
(f) Polar/arid.

For the last type of region, it is necessary to group the areas in which it does not seem currently possible to achieve completely acceptable densities because of sparse population, poor development of communications facilities, or for other economic reasons.

2.4.2.1 Climatological stations

The following types of data are collected at a climatological station in the basic network: precipitation, snow survey and evaporation. It is understood here that evaporation or snow-measuring stations, particularly the former, will generally measure temperature, humidity and wind because these meteorological elements affect evaporation and melting.

2.4.2.1.1 *Precipitation stations*

If one follows certain principles of installation and use, the small number of stations in the minimum network can furnish the most immediate needs. In general, precipitation gauges should be as uniformly distributed as is consistent with practical needs for data and the location of volunteer observers. In mountainous regions, attention must be given to vertical zonality by using storage gauges to measure precipitation at high altitudes. Precipitation gauges may be designed specifically to measure snow-water equivalent, either through the addition of shielding to reduce under-catch due to wind or through the use of pressure sensors. Periodic manual snow surveys may be used to supplement the network, but they should not be counted as part of the network.

The network should consist of three kinds of gauge:
(a) Standard gauges – These gauges are read daily for quantity. In addition to daily depth of precipitation, observations of snowfall, the depth of snow on the ground and the state of the weather are to be made at each standard precipitation station;
(b) Recorders – In developing networks, it is advisable to aim to have at least 10 per cent of such stations. The greatest density of recording stations should be achieved in those areas subject to intense, short-duration rainfalls. Such stations will provide valuable information on the intensity, distribution, and duration of precipitation.
For urban areas where the time resolution needed for rainfall measurements is of the order of one to two minutes, special attention should be paid to the time synchronization of the raingauges. For reliable measurements, tipping-bucket raingauges with an electronic memory (or another computer readable medium) are recommended.
In assigning priorities to locations for recording-raingauge installations, the following types of areas should be given priority: urban areas (population in excess of 10 000) where extensive drainage systems are likely to be constructed, river basins in which major river control systems are anticipated or are in operation, large areas inadequately covered by the existing network and special research projects;
(c) Storage gauges (totalizers) – In sparsely settled or remote regions, such as in desert or mountainous terrain, storage gauges may be used. These gauges are read monthly, seasonally, or whenever it is possible to inspect the stations.

Location of precipitation gauges relative to stream-gauging stations – To ensure that precipitation data are available for extending streamflow records, flood-forecasting purposes or hydrological analysis, coordination of the locations of the precipitation gauges with respect to those of the stream gauges is of great importance. Precipitation gauges should be located so that basin precipitation can be estimated for each stream-gauging station. These will usually be located at or near the stream gauge and in the upper part of the gauged drainage basin. A precipitation gauge should be located at the site of the stream gauge only if the observations will be representative of the general area. There can be cases in which it is desirable to locate the precipitation gauge some distance away from the stream gauge, as for instance when the stream gauge is in a narrow, deep valley.

2.4.2.1.2 *Snow surveys*

Where applicable, observations of snowfall, water equivalent of snow and depth of snow on the ground should be made at all precipitation stations in the minimum network.

The water equivalent of snow at the time of maximum accumulation is an indication of total seasonal precipitation in regions where winter thaws and winter snow melt are insignificant. In such regions, surveys of the snow cover on selected courses may be useful in estimating seasonal precipitation at points where the normal observations are unavailable. Such snow-cover surveys will also provide useful information for river forecasting and flood studies.

Snow-cover surveys are conducted by personnel equipped for sampling the accumulated snow and for determining its depth and water equivalent (3.5). The number of snow courses and their location and length will depend upon the topography of the catchments and the purposes for which the data are being collected. The full range of elevation and the types of exposure and vegetation cover in the area of interest should be considered in selecting representative courses. It is suggested that one course for 2 000 to 3 000 km^2 is a reasonably good density for less homogeneous regions, and one course for 5 000 km^2 in homogeneous and plain areas. However, each case must be considered on its own merits, and these generalities must not be applied indiscriminately.

In the early stages of network development, snow-cover surveys will usually be made only once a year, near the expected time of maximum accumulation. It will be desirable, later on, to extend the operation to include surveys at regular intervals throughout the snowfall season. As soon as it becomes feasible, these periodic snow surveys should be augmented by regular measurements of snow precipitation and observations of related meteorological factors, such as radiation, soil temperature and wind velocity.

2.4.2.1.3 *Evaporation stations*

Evaporation can be estimated indirectly in the water-budget, energy-budget and aerodynamic approaches, by extrapolation from pan measurements or directly through use of eddy-correlation equipment (Chapter 4). An evaporation station consists of a pan of standard national design where daily observations of evaporation are made, together with daily observations of precipitation, maximum and minimum water and air temperatures, wind movement and relative humidity or dewpoint temperature.

Evaporation plays an important role for long-term studies of the water regime of lakes and reservoirs and for water management. In such cases, the number and distribution of evaporation stations are determined according to the area and configuration of the lakes and the climatic region or regions involved.

2.4.2.2 Hydrometric stations

2.4.2.2.1 *Streamflow stations*

The main objective of the stream-gauging network is to obtain information on the availability of surface-water resources, their geographical distribution and their variability in time. Magnitude and frequency of floods and droughts are of particular importance in this regard.

In general, a sufficient number of streamflow stations should be established along the main stems of large streams to permit interpolation of discharge between the stations. The specific location of these stations should be governed by topographic and climatic considerations. If the difference in flow between two points on the same river is not greater than the limit of error of measurement at the station, then an additional station is unjustified. In this context, it must also be stressed that the discharge of a small tributary cannot be determined accurately by subtracting the flows at two main stream-gauging stations that bracket the mouth of the tributary. Where the tributary flow is of special interest in such a case, a station on the tributary will be required. It will usually take its place as a secondary station in the minimum network. The streamflow stations may be interspersed with stage stations (2.4.2.2.2).

Wherever possible, the base stations should be located on streams with natural regimes. Where this is impractical, it may be necessary to establish additional stations on canals or reservoirs to obtain the necessary data to reconstruct the natural flows at the base stations. Computed flows past hydro-electric plants or control dams may be useful for this purpose, but provisions will have to be made for calibration of the control structures and turbines and for the periodic checking of such calibrations during the life of the plants.

Stations should be located on the lower reaches of the major rivers of the country, immediately above the river mouths (usually above tidal influence) or where the rivers cross borders. Stations should also be located where rivers issue from mountains and above the points of withdrawal for irrigation water. Other hydrometric stations are situated at locations, such as where the discharge varies to a considerable extent, below the points of entry of the major tributaries, at the outlets from lakes, and where large structures are likely to be built. Hydrometric stations are often established at major cities to meet a number of societal needs.

To ensure adequate sampling, there should be at least as many gauging stations on small streams as on the main streams. However, a sampling procedure for small streams becomes necessary, as it is impracticable to establish gauging stations on all of them. The discharge of small rivers is strongly influenced by local factors. In highly developed regions, where even the smallest watercourses are economically important, network deficiencies are keenly felt even on streams draining areas as small as 10 km^2.

Stations should be installed to gauge the runoff in different geologic and topographic environments. Because runoff varies greatly with elevation in mountains, the basic network stations must be located in such a way that they can, more or less evenly, serve all parts of a mountainous area, from the foothills to the higher regions. Account should be taken of the varying exposure of slopes, which is of great significance in rough terrain, and to land cover, which may vary with exposure and other factors. Similarly, consideration should be given to stations in districts containing numerous lakes, the influence of which can be determined only through the installation of additional stations.

2.4.2.2.2 *River stages*

Stage (height of water surface) is observed at all stream-gauging stations to determine discharge. There are places where additional observations of water level only are needed as part of a minimum network:

(a) At all major cities along rivers, river stages are used for flood forecasting, water supply and transportation purposes;
(b) On major rivers, at points between stream-gauging stations, records of river stage may be used for flood routing and forecasting purposes.

2.4.2.2.3 *Lake and reservoir stages*

Stage, temperature, surge, salinity, ice formation, etc., should be observed at lake and reservoir stations. Stations should be established on lakes and reservoirs with surface areas greater than 100 km^2. As in the case of rivers, the network should sample some smaller lakes and reservoirs as well.

2.4.2.2.4 *Sediment discharge and sedimentation*

Sediment stations may be designed either to measure total sediment discharge to the ocean or to measure the erosion, transport and deposition of sediment within a country, basin, etc. In designing a minimum network, emphasis should be placed on erosion, transport and deposition of sediment within a country. An optimum network would contain a sediment station at the mouth of each important river discharging into the sea.

Sediment transport by rivers is a major problem in arid regions, particularly in those regions underlain by friable soils and in mountainous regions where, for engineering applications, the amount of sediment loads should be known.

The designer of a basic network must be forewarned that sediment-transport data are much more expensive to collect than other hydrological records. Consequently, great care must be exercised in selecting the number and location of sediment-transport stations. Emphasis should be placed on those areas where erosion is known to be severe. After a few years of experience, it may be desirable to discontinue sediment measurements at those stations where sediment transport no longer appears to be of importance.

Sediment-transport data may be supplemented by surveys of sediment trapped in lakes or reservoirs. Echo-sounding devices are useful for this purpose. However, information obtained in this way is not considered a substitute for sediment-transport measurements at river stations. Sediment discharge measurement and the computation of sediment load are covered in 5.5.

2.4.2.2.5 *Water-quality stations*

The usefulness of a water supply depends, to a large degree, on its chemical quality. Observations of chemical quality, for the purposes of this Guide, consist of periodic sampling of water at stream-gauging stations and analyses of the common chemical constituents. ISO Technical Committee 147 has prepared over 200 international standards pertaining to field sampling for water-quality and analytical methods.

The number of sampling points in a river depends on the hydrology and the water uses. The greater the water-quality fluctuation, the greater the frequency of measurement required. In humid regions, where concentrations of dissolved matter are low, fewer observations are needed than in dry climates, where concentrations, particularly of critical ions such as sodium, may be high.

2.4.2.2.6 *Water temperature*

The temperature of water should be measured and recorded each time a hydrometric station is visited to measure discharge or to obtain a sample of the water. The time of day of the measurement should also be recorded. At stations where daily stage observations are made, temperature observations should also be made daily. These observations, the cost of which is negligible, may provide data which are useful in studies of aquatic life, pollution, ice formation, sources of cooling water for industry, temperature effects on sediment transport, solubility of mineral constituents, or climate change.

2.4.2.2.7 *Ice cover on rivers and lakes*

Regular observations of ice cover should include the following:
(a) Visual observations of various processes of ice formation and of ice destruction, with recording of date of first occurrence of floating ice, date of total cover, date of break-up of the ice, and date at which the ice has vanished completely. These observations should be made on a daily basis;
(b) Simultaneous measurement of ice thickness at two or three points near each selected hydrometric station should be made once every 5 to 10 days. The location of measurement points is chosen from detailed surveys of ice cover made at the beginning of the observing period of the stations.

2.4.3 **Specific requirements for water quality**

There are several approaches to water-quality monitoring. Monitoring can be accomplished through a network of strategically located long-term stations, by repeated short-term surveys, or by the most common approach, a combination of the two. In addition to the basic objectives of the programme, the location of stations should take into account the following factors:
(a) Existing water problems and conditions;
(b) Potential growth centres (industrial and municipal);
(c) Population trends;
(d) Climate, geography and geology;
(e) Accessibility;
(f) Available human resources, funding, field and laboratory data handling facilities;
(g) Inter-jurisdictional considerations;
(h) Travel time to the laboratory (for deteriorating samples);
(i) Safety of personnel.

The design of a sampling programme should be tested and assessed during its initial phase to ensure the effectiveness and efficiency with respect to the objectives of the study.

2.4.3.1 **Water-quality parameters**

The parameters that characterize water quality may be classified in several ways, including physical properties (for example, temperature, electrical conductivity, colour and turbidity), inorganic chemical components (for example, dissolved oxygen, chloride, alkalinity, fluoride, phosphorous and metals), organic chemicals (for example, phenols, chlorinated hydrocarbons, polycyclic aromatic hydrocarbons and pesticides), and biological components, both microbiological, such as faecal coliforms, and macrobiotic, such as worms, plankton and fish, which can indicate the ecological health of the aquatic environment.

A second classification is done according to the importance attached to the parameter. This will vary with the type of water body, the intended use of the water and the objectives of the monitoring programme. Water-quality variables are sometimes grouped into two categories:
(a) Basic variables (Table I.2.7) (UNEP, 2005);
(b) Use-related variables:
    (i) Drinking water supplies;
    (ii) Irrigation;
    (iii) General quality for aquatic life.

A third classification that is highly relevant to sampling procedures is done according to stability:

(a) Conservative (does not change materially with time);
(b) Non-conservative (changes with time, but can be stabilized for at least 24 hours by appropriate treatment); or
(c) Non-conservative (changes rapidly with time and cannot be stabilized).

The first two groups can be measured by representative water samples subsequently analysed in the laboratory. The third group needs to be measured in situ.

2.4.3.2 Surface-water quality

Sometimes the programme objectives will precisely define the best locations for sampling in a river or lake system. For example, in order to determine the effect of an effluent discharge on a receiving stream, sampling locations upstream and downstream of the discharge would be required. In other cases, both location and frequency of sampling will be determined by anti-pollution laws or by a requirement for a specific use of a water body. For example, a permit to discharge surface waters may outline details of monitoring, such as location, number of samples, frequency and parameters to analyse. Water-quality monitoring programmes may be

Table I.2.7. GEMS/Water basic variables

Water quality category	*GEMStat parameters*	
Hydrological and sampling variables	Instantaneous discharge	
Physical/Chemical variables	Water discharge/level (GRF) Total suspended solids (R) Temperature pH (GRF)	Electrical conductivity Dissolved oxygen Transparency (L)
Major ions Dissolved salts/Ionic balance	Calcium Magnesium Sodium Potassium Chloride Fluoride (GW)	Sulphate Alkalinity Sum of cations Sum of anions Sodium adsorption ratio
Nutrients	Nitrate plus nitrite Ammonia Organic nitrogen, dissolved Organic nitrogen, particulate	Total phosphorus, dissolved (R, L) Total phosphorus, particulate Total phosphorus, unfiltered (R, L) Silica reactive (R, L)
Organic matter	Organic carbon, dissolved Organic carbon, particulate BOD	COD Chlorophyll *a* (R, L)
Microbiology	Faecal coliform Total coliforms	Giardia Cryptospiridium
Metals Inorganic contaminants (measured as dissolved, particulate, and/or total; particulate concentrations are essential for GRF stations)	Aluminium Arsenic Boron Cadmium Chromium Copper Iron	Lead Manganese Mercury Nickel Selenium Zinc
Organic contaminants	Aldicarb Aldrin Altrazine Benzene 2, 4-D DDTs Dieldrin Lindane	Total hydrocarbons Total chlorinated hydrocarbons Total polyaromatic hydrocarbons PCBs PBDEs (polybrominated diphenyl ethers) Phenols Toxaphene

R Basic variables for river stations only
L Basic variables for lake/reservoir stations only
GW Basic variables for groundwater stations only
R, L Basic variables for river, lake/reservoir stations only
GRF Essential for global river flux monitoring stations

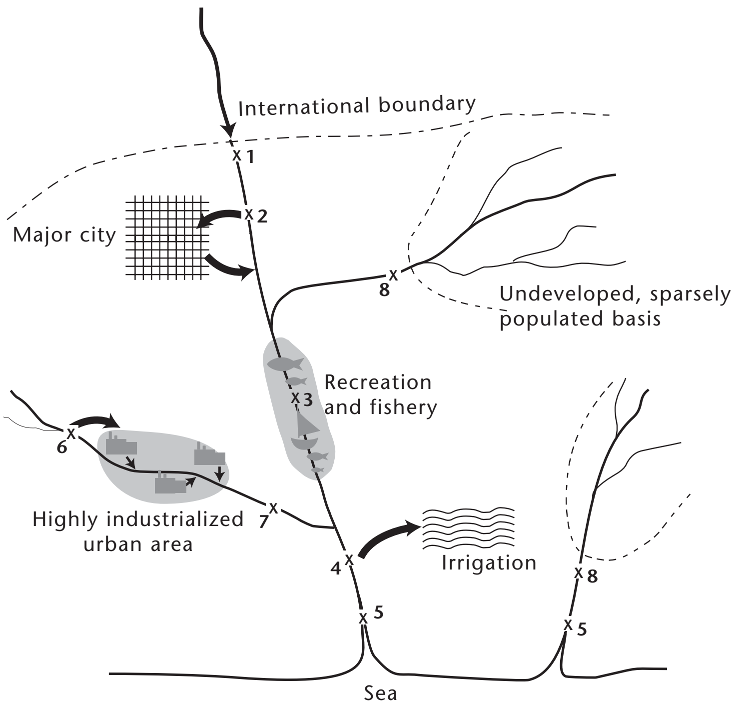
supplemented by intensive, but infrequent, special purpose water-quality surveys aimed at understanding short-term fluctuations in water-quality parameters. As well, special situations may call for water-quality surveillance, the continuous, specific measurement of selected parameters.

Sampling strategies vary for different kinds of water bodies and media, for example, water, sediment, or biota. Rivers mix completely within distances ranging from several kilometres to a few hundred kilometres of any point source of pollution. Lakes may be vertically stratified because of temperature or inflows of high-density saline water. Groundwater tends to flow very slowly, with no surface indication of the changes in its solutes taking place below.

If the objective concerns the impact of human activities on water quality in a given river basin, the basin can be separated into natural and altered regions. The latter can be further subdivided into stationary zones for instance, over periods longer than 10 years, and those in which the impact is variable, such as agricultural, residential and industrial zones. In acid-deposition studies, an important factor is the terrain sensitivity to the deposition. Figures I.2.7 and I.2.8 provide some examples of where and how sampling stations could be located to meet specific objectives on river and lake systems.

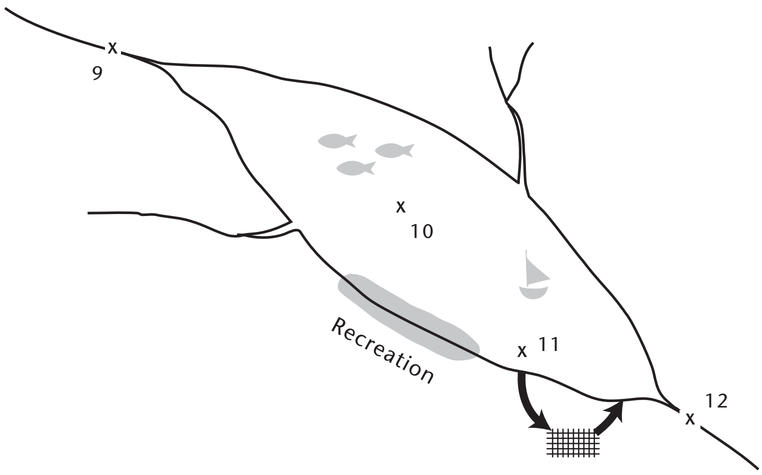
The next step in choosing sampling locations is to collect relevant information about the region to be monitored. The information sought includes geological, hydrological and demographic aspects, as well as the number of lakes and streams, size and locations of aquifers, locations of existing water-quality or stream-gauging stations, flow rates, climatic conditions in the catchment area, historical developments, present and potential municipal and industrial centres, current water intakes and waste outlets, natural salt springs, mine drainage, irrigation schedules, flow regulation (dams), present and planned water uses, stream or lake water-quality objectives or standards, accessibility of potential sampling sites (land ownership, roads and airstrips), availability of services such as electricity, and existing wate-quality data. Figure I.2.9 shows the steps to be followed in selecting sampling sites. The distance downstream to the point of complete mixing is roughly proportional to the stream velocity and to the square of the width of the channel. Rivers are usually sufficiently shallow that vertical homogeneity is quickly attained below a source of pollution. Lateral mixing is usually much more slowly attained. Thus, wide swift-flowing rivers may not be completely mixed for many kilometres downstream from the input point.

Various protocols are recommended to determine representative sampling in the cross-section of the river, for example, six samples analysed in duplicate,



Station	*Criteria*
1	Immediately downstream of an international boundary
2	Diversion for public supply of large town
3	Important fishing, recreation and amenity zone
4	Diversion for large-scale agricultural irrigation
5	Freshwater tidal limit of major river
6	Diversion for large industrial supply
7	Downstream of industrial effluent discharges and important tributary influencing main river
8	Baseline station, water in natural state

Figure I.2.7. Monitoring site: rivers



Station	*Criteria*
9	Principal feeder tributary
10	General water quality of lake
11	Water supply for major city
12	Water leaving lake

Figure I.2.8. Monitoring site: lakes

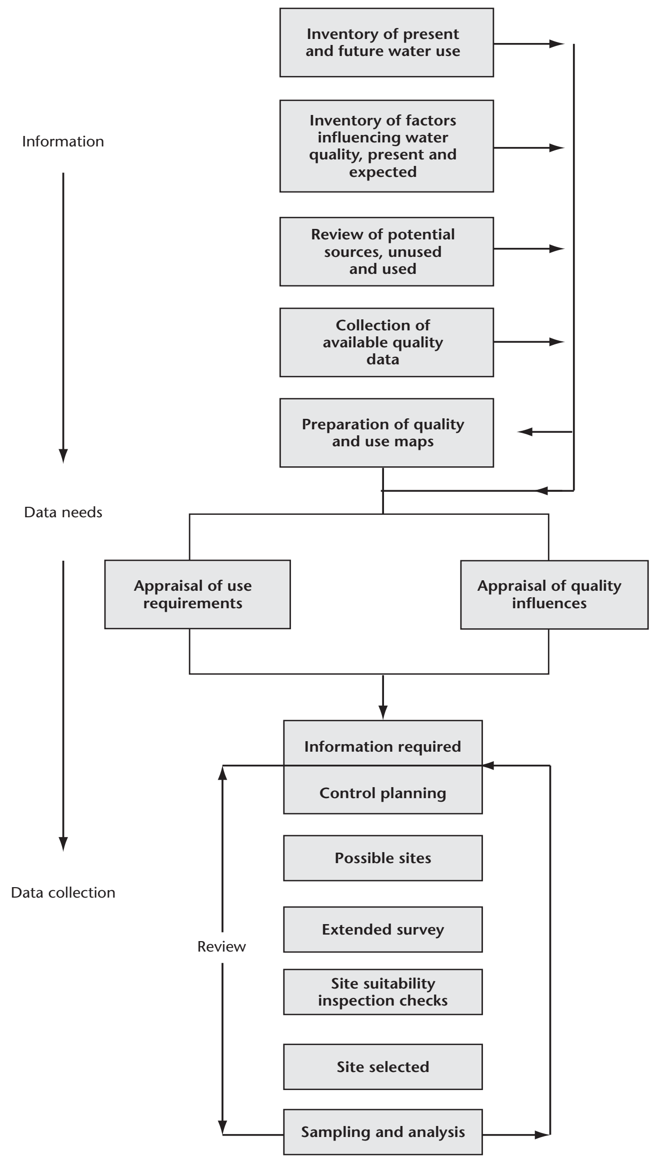


Figure I.2.9. Scheme for the selection of water quality sampling sites

at three positions across the river and two depths or mid-depth samples at the quarter points, or other equal distance points across the width of the river. If a representative sample cannot be obtained, it is advisable to select another site, either immediately upstream or downstream. The other alternative is to obtain a flow-weighted composite sample from samples collected on cross-section verticals.

Longitudinal mixing of irregular or cyclic discharges into a river will have a secondary influence on the location of a sampling site. Their effects need to be taken into account in deciding the frequency of sampling and interpreting data.

Sampling frequency depends on the purpose of the network, the relative importance of the sampling station, the range of measured values, the time variability of the parameter of interest and the availability of resources. In the absence of sufficient background information, an arbitrary frequency based on knowledge of local conditions is chosen. After sufficient data have been collected, the frequency may be adjusted to reflect the observed variability. The frequency is also influenced by the relative importance of the station and whether or not the concentrations approach critical levels for some substances measured.

For lake stations, the recommended practice is to sample five consecutive days during the warmest part of the year and five consecutive days every quarter. Special cases include temperate-zone lakes that experience stratification. These should be sampled at least six times a year, together with the occasional random sample, to cover the following periods: during open water prior to summer stratification, during mixing following summer stratification, under ice, and during the periods of snow melt and runoff. Similarly, additional samples of rivers should be taken, if possible, after storm events and during snow melt and runoff.

When parameters are plotted against time, some cyclic variation may be apparent amidst the random fluctuations. The detection of cyclic events requires a sampling interval no longer than one third of the shortest cycle time and sampling over a period at least ten times longer than the time of the longest cycle. Therefore, long-period cycles will not be verified in the initial surveys, but become apparent during the operation of the network. In order to detect the cyclic variations, some random sampling is desirable, for example, on different days of the week or different hours of the day.

2.4.3.3 Precipitation quality

In general, sampling sites should be selected to give accurate and representative information concerning the temporal and spatial variation of chemical constituents of interest. Important factors to take into consideration are prevalent wind trajectories, sources for compounds of interest, frequency of precipitation events (rain, snow, hail), and other meteorological processes that influence the deposition. There are also local criteria to be considered:

(a) No moving sources of pollution, such as routine air, ground, or water traffic, should be within 1 000 m of the site;
(b) No surface storage of agricultural products, fuels, or other foreign materials should be within 1 000 m of the site;
(c) Samplers should be installed over flat undisturbed land, preferably grass-covered, surrounded by trees at distances greater than 5 m from the sampler. There should be no wind-activated sources of pollution nearby, such as cultivated fields or unpaved roads. Zones of strong vertical eddy currents, eddy zones leeward of a ridge, tops of windswept ridges and roofs of buildings, particularly, should be avoided because of strong turbulence;
(d) No object taller than the sampler should be within 5 m of the site;
(e) No object should be closer to the sampler than a distance of 2.5 times the height by which the object extends above the sampler. Particular attention must be given to overhead wires;
(f) The collector intake should be located at least 1 m above the height of existing ground cover to minimize coarse materials or splashes from being blown into it;
(g) Automatic samplers require power to operate lids and sensors, and in some cases for refrigeration in the summer and thawing in the winter. If power lines are used, they must not be overhead. If generators are used, the exhaust must be located well away and downwind from the collector;
(h) To address issues on a continental scale, sites should preferably be rural and remote, with no continuous sources of pollution within 50 km in the direction of the prevalent wind direction and 30 km in all other directions.

It may not be possible to meet all of these criteria in all cases. The station description should refer to these criteria and indicate the exact characteristics of each location chosen as a sampling site.

In the case of large lakes, the precipitation over the lake may not be as heavy as along the shores and the proportion of large particles may be smaller. In order to sample in the middle of a lake, the sampler can be mounted on a buoy, rock, shoal or small island.

Event sampling is the preferred method for sampling precipitation. Each rain shower, storm or snowfall constitutes an event. The analysis of event-precipitation samples enables pollutants associated with a particular storm to be determined, and a wind-trajectory analysis can determine probable sources. However, this sampling regime is very sensitive. The same statistical considerations concerning frequency of sampling apply here as for surface-water sampling.

2.4.3.4 Sediment quality

Most of the selection criteria outlined in previous sections also apply to sampling for sediment. Therefore only additional special recommendations will be described here.

For rivers where sediment-transport data are required, it is necessary to locate the sampling sites near a water quantity gauging station so that accurate stream discharge information is available at all times. Sampling locations immediately upstream from confluences should be avoided because they may be subjected to backwater phenomena. In streams too deep to wade, locate sampling sites under bridges or cableways. When sampling from bridges, the upstream side is normally preferred. Sampling in areas of high turbulence, such as near piers, is often unrepresentative. Attention also must be paid to the accumulation of debris or trash on the piers, as this can seriously distort the flow and hence the sediment distribution. An integrated sample obtained by mixing water from several points in the water column according to their average sediment load can be considered as a representative sample as long as there is good lateral mixing.

The best places to sample bottom deposits in fast-flowing rivers are in shoals, at channel bends and at mid-channel bars or other sheltered areas where the water velocity is at its minimum.

Sampling sites should be accessible during floods, since sediment-transport rates are high during these times.

For identification of peak pollution loads in rivers, two cases must be considered:

(a) For pollution from point sources, sampling should be done during low-flow periods, when pollution inputs are less diluted;
(b) When pollutants originate from diffuse sources such as runoff from the land of agricultural nutrients or pesticides, sampling must be focused on flood periods during which the pollutant is washed out of the soil.

If one of the objectives is to quantify the transport of sediment in the river system, it should be noted that peak concentrations of sediment do not necessarily correspond with times of peak flow. Also, a series of high flow rates will lead to progressively lower sediment peaks – an exhaustion effect arising from the depletion of material available for re-suspension.

For lakes, the basic sampling site should be located at the geographic centre of the lake. If the lake is very large (area > 500 km^2), several base stations may be needed. If various sediment types must be sampled, then data from acoustic surveys (echo-sounders) can be used both to identify the type of surficial material (sand, gravel or mud) and to indicate the presence of layering below the surface. Secondary sampling sites should be located between the base station and major tributary inlets or pollutant sources. A common strategy is to place points down the long axis of the lake with occasional cross-lines. Three to five stations should usually give a good approximation to the sediment quality of an average size lake. For statistical validity, however, a larger number of sampling sites will probably be required.

Sampling frequency in lakes is affected by the generally low concentrations of suspended sediment. Sediment traps should be operated during periods of maximum and minimum algal productivity and at times of high input of sediment from rivers.

Repeat sampling of bottom sediments in lakes needs to take into account the rates of sediment accumulation. Basins in cool temperate climates often have accumulation rates in the order of 0.1–0.2 mm per year. A resampling period of five years would then be too soon to provide worthwhile new information, unless the presence of a new pollutant is to be tested.

2.4.3.5 Groundwater quality

A great deal of hydrogeological information may be necessary to plan the sampling strategy for aquifers. Water levels, hydraulic gradients, velocity and direction of water movements should be known.

An inventory of wells, boreholes and springs fed by the aquifer should be drawn up, and details of land use should be recorded.

Groundwater samples are taken from drainage water, open wells and drilled wells. Wells should be sampled only after they have been pumped long enough to ensure that a fresh sample has been obtained. This is particularly necessary where a well has a lining subject to corrosion.

An existing well is a low-cost choice, although wells are not always at the best location or made of non-contaminating materials. A well that is still in use and pumped occasionally is preferable to one that has been abandoned. Abandoned or unused wells are often in poor condition with damaged or leaky casings and corroded pumping equipment. It is often difficult to measure their water levels, and they may be safety hazards.

Changes in groundwater quality can be very slow and are often adequately described by monthly, seasonal or even annual sampling schedules.

2.4.4 Operational data acquisition networks

Many types of hydrological forecasts are compiled on the basis of data from networks. Information may include measurements, as well as details of the operation of water-management and flood-protection works. A forecast system should make use of data from the basic network (2.4.1.3) as far as possible. The scope of the forecast network is determined by:

(a) User demands for forecasts at specified locations and for current information on the status of water bodies;
(b) The network density needed to describe the hydrological characteristics and the dimensions of water bodies;
(c) The technology for data transmission to the forecast centre;
(d) The representativeness of the observations;
(e) The media for issuing forecasts.

The information on water-management operations should be organized to fit in with the normal operational routines of the water-management agencies that supply the information.

A schedule of reports transmitted to the forecast centre by non-automatic monitoring stations should be drawn up, and the reports should be classified according to whether they are regularly or occasionally transmitted. The regular reports should include daily information on water levels, discharge and temperature and, where appropriate, ice phenomena, as well as observations every 5 or 10 days on ice thickness, snow depth and water equivalent. The occasional reports contain emergency information on significant changes in the regime of water bodies and operational control strategies, as well as specially requested reports that are needed to define the development of particular hydrological phenomena.

The *Casebook on Hydrological Network Design Practice* (WMO-No. 324) gives examples of spatial densities for various hydrological variables and the general principles for determining them based on the time and space variability.

2.4.5 Network-strategy options

In addition to seeking to improve representativeness of existing surface-water data networks, Hydrological Services should develop more comprehensive monitoring strategies. For selected basins, the hydrometric data-collection activities need to be integrated with sediment, water quality, meteorology and aquatic-habitat programmes (2.4.1.4). For example, concerns for sediment-associated contaminant transport require knowledge of the source, pathways and fate of fine particles. This requires an understanding of both the flow and sediment regimes. Whether for the interpretation of concentrations or for calculating contaminant loadings, such integrated monitoring requires close coordination at all stages from planning to reporting.

Integrated planning of related data networks should be developed to maximize the effectiveness of all water-data programmes. Significant efforts are required to define network needs from many different perspectives, and, ultimately, to coordinate the data collected on a watershed basis so that adequate water data, that is, precipitation, runoff, groundwater and water quality, are available to meet future needs.

Present monitoring programmes can be enhanced by the use of supplementary studies. For example, river studies of sediment sources and morphologic change (Church and others, 1989; Carson, 1987) supplement regular programme data to determine the river behaviour. This knowledge, which is not acquired from monitoring studies alone, is being used for fisheries management, river-engineering studies and water-quality studies.

On a different scale, water-quality considerations are increasingly important to urban drainage design.

The design of appropriate monitoring programmes should consider short-interval sampling, integrated precipitation and runoff monitoring, and extremely rapid response times if the data are to be useful. These conditions are quite different from those covered by standard monitoring procedures. The use of computer models is an additional strategy for enhancing the information derived from water-monitoring activities. In certain circumstances, monitoring-network designs can be improved by the use of models.

2.5 DATA COLLECTION

2.5.1 Site selection

Once the network design phase has been completed, the operational requirements have established the general location of the data-collection sites, and the types of instrumentation have been identified, the best specific site in the general location is selected to meet the requirements of the instrumentation as outlined in subsequent chapters of this Volume (5.3.2.1 and 5.4.2). Modifications to the site may be necessary to ensure the quality of the data, for example, clearing and control stabilization.

When a site has been selected and the instrumentation has been installed, two types of data will be collected at the site: descriptive details of the site and its location, and the hydrological observations that it has been established to measure. Once established, the installation should be operated and maintained to its predetermined standard. In general, this involves the execution of an adequate schedule of inspection and maintenance to ensure continuity and reliability of data, and the development of routine check measurements and calibrations to ensure data of the required accuracy.

2.5.2 Station identification

Two aspects should be considered to ensure the historical documentation of details of a data-collection site: the institution of an identification system and the archival of descriptive information.

2.5.2.1 Identification of data-collection sites

Every permanent site should be given a unique identifier that will be used to denote all data and other information pertinent to the site. Such identifiers are usually numeric, but they may also be alphanumeric.

Frequently, more than one service or agency may be operating data-collection sites in one particular region or country. The acceptance by all parties of a single, unique system of site identification will facilitate data interchange and the multiparty coordination of data-collection activities. The region chosen should be determined by drainage basin(s) or climatic zones, and part of a site's identification should reflect its location in the region.

The site identification can be simply an accession number, that is, a sequential number assigned as stations are established. For example, site identification in the Canadian National Water Quality Data Bank, NAQUADAT, represents a sophisticated system designed for computer processing. It has a 12-digit alphanumeric code, which is the key element in storing and retrieving data in the computer system. This number is composed of several subfields (UNEP/WHO, 1996), as follows:

(a) Type of water – a two-digit numerical code indicating the type of water sampled at any given location, such as streams, rivers and lakes, or precipitation. The meaning of this code has been extended to include other types of aquatic media. A list of all currently assigned codes is given in Table I.2.8;
(b) Province, basin and sub-basin – three pairs of digits and letters identifying the province, basin and sub-basin;
(c) Sequential – a four-digit number assigned usually by a regional office.

For example, station number 00BC08NA0001 indicates that the sampling site is on a stream, in the province of British Columbia, in basin 08 and in sub-basin NA, and the sequence number is 1. Station number 01ON02IE0009 is on a lake, in the province of Ontario, in basin 02 and in sub-basin IE and the sequence number is 9.

WMO has accepted a coding system for station identification (Moss and Tasker, 1991) that is similar to (b) and (c) of the NAQUADAT system.

Another well-known coding system for sampling points is the River Mile Index used by the Environmental Protection Agency of the United States as part of the STORET system. In this system, the location of a sampling point is defined by its distance and hydrological relationship to the mouth of a river system. It includes major and minor basin codes, terminal stream numbers, the direction and level of streamflow, the mileages between and to confluences in the river system, and a code to identify the stream level on which the point is located.

Table I.2.8. NAQUADAT codes for types of aquatic media

Type	*Code*	*Subtype*	*Code*
Surface water	0	Stream-channel	0
		Lake	1
		Estuary	2
		Ocean-sea	3
		Pond	4
		Impounded reservoir	5
		Harbour	6
		Ditch	7
		Runoff	8
		Unknown	9
Groundwater	1	Well-sump	0
		Spring	1
		Piezometer well	2
		Tile drain	3
		Bog	4
		Household tap	8
		Unknown	9
Waste-treated	2	Industrial	0
		Municipal	1
		Mining	2
		Livestock waste	3
		Unknown	9
Precipitation	3	Rain	0
		Snow	1
		Ice (precipitated)	2
		Mixed precipitation	3
		Dry fallout	4
Treated supply	4	Municipal	0
		Industrial	1
		Mining	2
		Private (individual)	3
		Other communal works	4
		Municipal distribution	5
		Municipal treatment plant (intermediate)	6
		Treatment residue or sludge	7
		Other	9

Type	*Code*	*Subtype*	*Code*
Sediments, soils	5	Stream channel	0
		Lake bottom	1
		Stream bank	2
		Lake bank	3
		Contaminated by soil	4
		General soil	5
		Effluent irrigation soil	6
		Sludge or conditioned soil	7
		Other	8
Industrial waste water	6	Storm water	0
		Primary influent	1
		Primary effluent	2
		Final effluent	3
		Sludge	4
		Special problem	5
		Other	6
Municipal waste water	7	Raw	0
		Primary lagoon effluent	1
		Secondary lagoon effluent	2
		Conventional primary effluent	3
		Conventional secondary effluent	4
		Advanced waste water treatment effluent	5
		Disinfected effluent	6
		Raw sludge	7
		Digested sludge	8
		Other	9
Miscellaneous waste water	8	Raw	0
		Primary lagoon effluent	1
		Secondary lagoon effluent	2
		Conventional primary effluent	3
		Conventional secondary effluent	4
		Advanced waste water treatment effluent	5
		Disinfected effluent	6
		Raw sludge	7
		Digested sludge	8
		Other	9

Source: World Meteorological Organization, 1988*a*: *Manual on Water Quality Monitoring – Planning and Implementation of Sampling and Field Testing*. Operational Hydrology Report No. 27, WMO-No. 680, Geneva.

2.5.2.2 Descriptive information

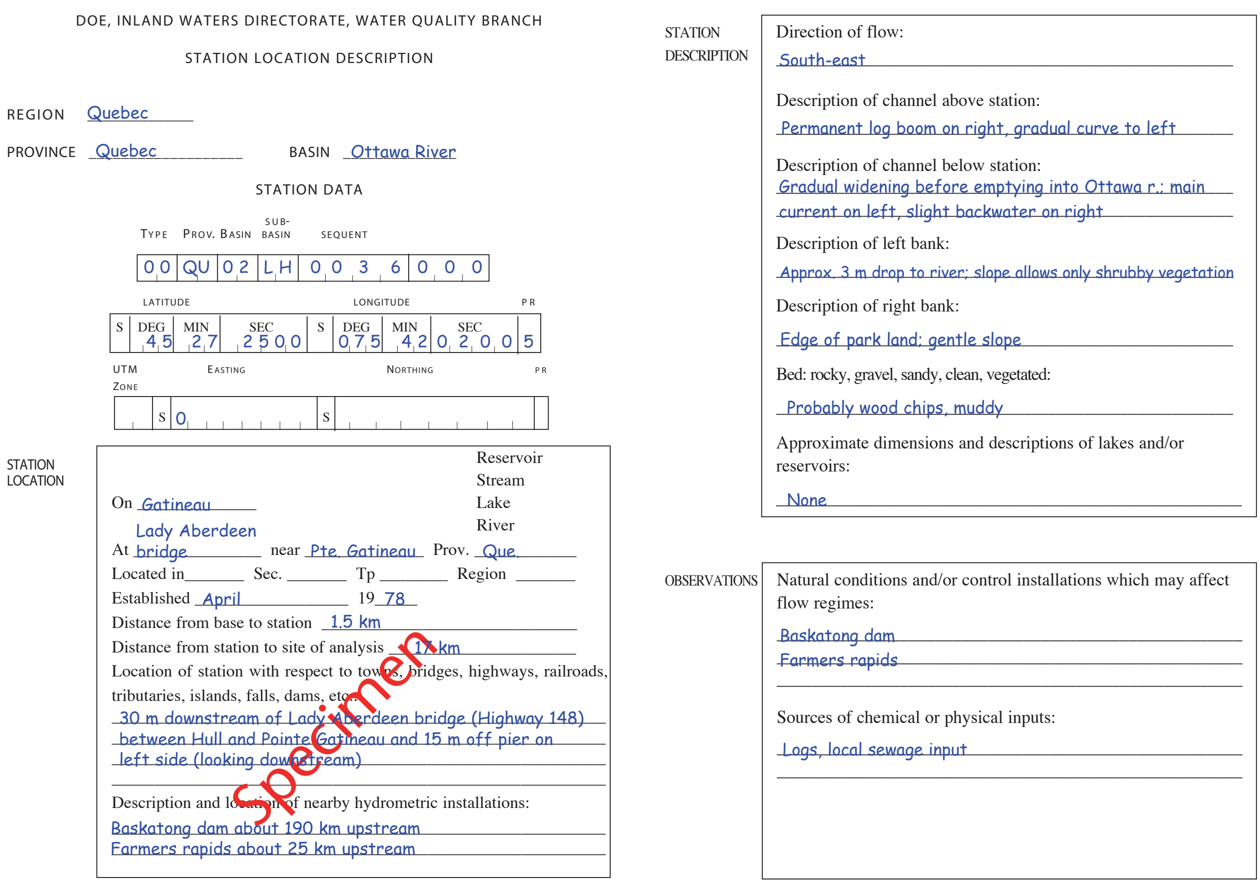
In many instances the value of the data will be enhanced if the user can relate it to the details of the history of its collection as part of the routine production of metadata. To this end, a station registration file should record the details of each station. The level of detail will of course vary with the parameter monitored. Typical information would include the station name and location details, the station type, the associated stations, establishing/operating/owner authorities, the elevation details, the frequency of observation, the operating periods and the details of installed equipment. Additional items specific to the station type should also be included. Selected information from this text file should be attached routinely to any data output (Chapter 10).

A historical operations file of more detailed information should also be prepared for release as required (Chapter 10). Again, the level of detail will vary with the type of observations being recorded. A stream station may include details such as climate zone and rainfall and evaporation notes, geomorphology, landforms, vegetation, land use and clearing, and station details. Typical components of such a file would include the station description, a detailed sketch of the site, a map showing the location of the site in the region, and a narrative description of the site and region. Some examples of the format of such files can be found in the UNEP (2005) and Environment Canada (1983) publications. Figure I.2.10 is an example of one format.

2.5.2.2.1 *Station description*

An accurate description of the sampling location includes distances to specific reference points. It is important that these reference points be permanent and clearly identified. For example, "5 metres north-west of the willow sapling" is a poor designation for a data site. An example of a useful description is "30 metres downstream from Lady Aberdeen Bridge (Highway 148), between Hull and Pointe Gatineau and 15 metres off the pier on the left side looking downstream". If hand-held global positioning devices are available, the geographic coordinates of the sampling location should be determined and recorded on the station description. The dates that the station was first established and that data collection was commenced should also be recorded.

For streamflow and water-quality data stations, location information should also include descriptions of the water body above and below the station. These should include water depths, a description of the banks on either side of the water body and the bed material. A description of the water body should include any irregularities in morphology that might affect the flow of water or its quality. Such irregularities may include a bend in a river, a widening or narrowing of the channel, the presence of an island, rapids or falls, or the entry of a tributary near the station. A description of the banks should mention slope, bank material and extent of vegetation. Bed or sediment material may be described as rocky, muddy, sandy, vegetation-covered, etc. Station-location descriptions


DOE, INLAND WATERS DIRECTORATE, WATER QUALITY BRANCH

STATION LOCATION DESCRIPTION

REGION Quebec

PROVINCE Quebec BASIN Ottawa River

STATION DATA

TYPE 00 PROV. QU BASIN 02 SUB-BASIN LH SEQUENT 003 6000

LATITUDE S DEG 45 MIN 27 SEC 2500 LONGITUDE S DEG 075 MIN 42 SEC 02005 PR

UTM ZONE S 0 EASTING S NORTHING PR

STATION LOCATION

On Gatineau (Reservoir / Stream / Lake / River)

At Lady Aberdeen bridge near Pte. Gatineau Prov. Que.

Located in ______ Sec. ______ Tp ______ Region ______

Established April 19 78

Distance from base to station 1.5 km

Distance from station to site of analysis 17 km

Location of station with respect to towns, bridges, highways, railroads, tributaries, islands, falls, dams, etc.:

30 m downstream of Lady Aberdeen bridge (Highway 148) between Hull and Pointe Gatineau and 15 m off pier on left side (looking downstream)

Description and location of nearby hydrometric installations:

Baskatong dam about 190 km upstream
Farmers rapids about 25 km upstream

Specimen

STATION DESCRIPTION

Direction of flow:
South-east

Description of channel above station:
Permanent log boom on right, gradual curve to left

Description of channel below station:
Gradual widening before emptying into Ottawa r.; main current on left, slight backwater on right

Description of left bank:
Approx. 3 m drop to river; slope allows only shrubby vegetation

Description of right bank:
Edge of park land; gentle slope

Bed: rocky, gravel, sandy, clean, vegetated:
Probably wood chips, muddy

Approximate dimensions and descriptions of lakes and/or reservoirs:
None

OBSERVATIONS

Natural conditions and/or control installations which may affect flow regimes:
Baskatong dam
Farmers rapids

Sources of chemical or physical inputs:
Logs, local sewage input

Figure I.2.10. Station-location forms

should mention seasonal changes that may hinder year-round data collection. Additional information in the case of lakes could include surface area, maximum depth, mean depth, volume and water residence time.

Additional information about conditions, either natural or man-made, which may have a bearing on the data should be recorded. Past and anticipated land disturbances and pollution sources should be mentioned, for example, forest fires, road construction, old mine workings, and existing and anticipated land use.

2.5.2.2.2 *Detailed sketch of station location*

A sketch of the location and layout of the station (including distances expressed in suitable units) with respect to local landmarks and permanent reference points, such as benchmarks, should be prepared (Figure I.2.11). Sampling or measuring sites and equipment locations should be prominently shown on the sketch.

2.5.2.2.3 *Map*

A large-scale map (Figure I.2.12) that locates the site with respect to roads, highways and towns should be included. The combination of the map and the sketch of the station location should provide complete location information. An investigator travelling to the site for the first time should have enough information to locate the station confidently and accurately.

2.5.2.2.4 *Coordinates*

Geographical coordinates are recorded as latitude and longitude and, in addition, coordinates may be recorded in other reference systems such as universal transverse mercator (UTM) coordinates or legal land descriptions. If the site is on a stream, its distance upstream from a reference point, such as a reference station or a river mouth should be recorded. National grid references, if available, should also be provided. For the international GLOWDAT (that is, GEMS/WATER data bank (UNEP, 2005) station), one entry is the WMO code for the octant of the globe for the northern hemisphere: 0, 1, 2 and 3 for 0–90°W, 90–180°W, 180–90°E and 90–0°E, respectively (WMO-No. 683). Correspondingly, for the southern hemisphere the codes are: 5, 6, 7 and 8 for 0–90°W, 90–180°W, 180–90°E and 90–0°E (WMO-No. 559).

Latitude and longitude values should be obtained using a global positioning system or, if that is not possible, from 1:50 000 or 1:250 000 topographical maps. Points on a 1:250 000 map can be located to about ±200 m and on a 1:50 000 scale to about ±40 m (WMO-No. 559). If available, navigational charts can be used to provide more accurate values than the topographical maps.

2.5.2.2.5 *Narrative description*

For streamflow and water-quality sites, it is recommended that the narrative description begin with the name of the river, stream, lake, or reservoir, followed by its location (for example, upstream or downstream) and its distance (to 0.1 km or better) from the nearest town, city, important bridges, highways or other fixed landmarks. The name of the province, territory or other geopolitical division should also be included.

Information concerning changes at the site, including instrumentation changes, should be added to the narrative description to provide a historical description of the site and the region that

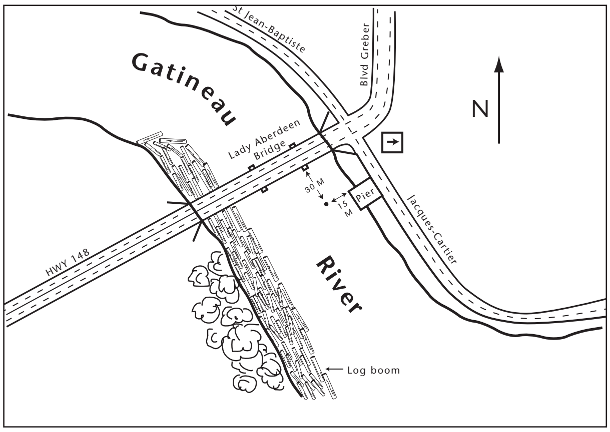


Figure I.2.11. Sketch of station layout

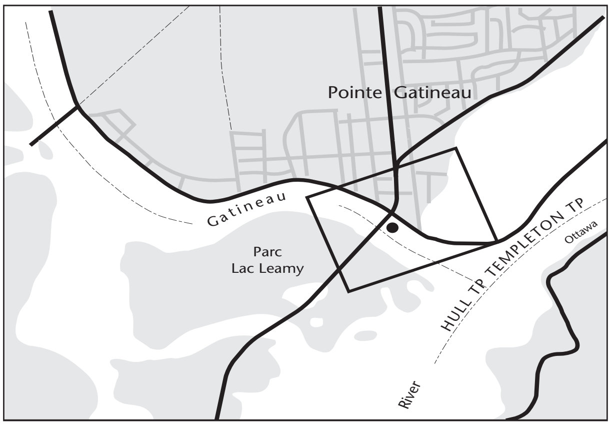


Figure I.2.12. Station-location map

it represents. Chapter 10 contains a suggested format for such information.

2.5.3 Frequency and timing of station visits

The frequency and timing of readings and thus visits to the site should be determined by the anticipated data usage and should be adequate to define the observations over time. Station visits will thus be for purposes of observation or collection of data and for maintenance of the site.

When the variable of interest at the site is changing rapidly, visits to manual stations must be more frequent if a valid record is to be maintained. Under such conditions, it may be more efficient to install automatic recording equipment or real-time transmission if funds and trained staff are available. This applies particularly where more frequent observations are desirable for hydrological purposes during storms and flood periods, as well as in tidal reaches of rivers.

2.5.3.1 Manual stations

There is considerable merit in encouraging the taking of observations at climatological stations at specified synoptic hours. WMO recommends (WMO-No. 544) that the time at which three-hourly and six-hourly weather observations are taken at synoptic stations are 0000, 0300, 0600, 0900, 1200, 1500, 1800 and 2100 universal time coordinated (UTC). In most countries, such stations are the key stations of the meteorological and climatological observation programmes. If the observer is to take three observations per day, the synoptic hours most conveniently related to normal times of rising and retiring and that nearest noon should be specified. For stations at which only one or two observations per day are taken, it should be possible to select synoptic hours for the observations.

It is recommended that all observers making only one observation per day should have a common observation time, preferably in the morning.

Some streams, for example small mountain-fed streams, may experience diurnal fluctuations in water levels during some seasons. Stage observations should initially be made several times a day at new stations to ensure that a single reading is an adequate representation of daily water level. Also, small streams may exhibit "flashy" behaviour in response to rain storms. Additional stage readings should be obtained during these times to adequately define the hydrograph. Stage observations should also be made at the time of water-quality sampling.

While it is desirable to have regular observations at synoptic hours, in some cases this will not be possible. In these cases, it is important that observations be taken at the same time each day and that this time be recorded in UTC or local standard time using 24-hour clock designations. If "summer time" (daylight saving time) is introduced for part of the year, arrangements should be made to have observations taken at the same hour, by UTC, as in the period prior to and following "summer time".

The designated time of climatological observations should be the end of the time at which the set of observations is taken at a station. The set of observations should be taken, if possible, within the 10-minute period prior to the stated observational time. However, it is important that the actual time of observation be recorded carefully, whether the observation is taken at a standard time or not. In tidal reaches of rivers, the times of observation should be related to the tidal cycle.

2.5.3.2 Recording stations

The frequency and timing of visits to recording stations will be constrained by the length of time that the station can be expected to function without maintenance. For example, some continuous rainfall recorders record on a weekly strip chart and, thus, require weekly visits to remove and replace charts. Other instruments have much larger data storage capabilities and, therefore, require less frequent visits. A balance must be achieved between the frequency of the visits and the resultant quality of the data collected. Too long a time between visits may result in frequent recorder malfunction and, thus, in loss of data, while frequent visits are both time consuming and costly. Various studies have been carried out on the cost-effectiveness and efficiency of data collection. Further details are found in the *Proceedings of the Technical Conference on the Economic and Social Benefits of Meteorological and Hydrological Services* (WMO-No. 733).

The frequency of the visits may also be determined by accuracy requirements of the data. Some data-collection devices may suffer a drift in the relationship between the variable that is recorded and that which the recorded value represents. An example of this is a non-stable stage-discharge relationship. In such cases, visits to the station are required periodically in order to recalibrate the equipment or the measurement equations.

2.5.3.3 New technologies

The introduction of data loggers and telephone/satellite data transmission may have a significant impact on station inspection/data-collection frequencies (2.5.6). However, it should be noted that in order to ensure the quality of the data, regular station maintenance is necessary.

2.5.4 Maintenance of sites

The following maintenance activities should be conducted at data-collection sites at intervals determined to ensure that the quality of the data being recorded is adequate. These activities could be conducted by the observer responsible for the sites, if there is one. However, they should occasionally be performed by an inspector (9.8.4).

All collection sites:
(a) Service the instruments;
(b) Replace or upgrade instruments, as required;
(c) Retrieve or record observations;
(d) Perform the recommended checks on retrieved records;
(e) Carry out general checks of all equipment, for example, transmission lines;
(f) Check and maintain the site to the recommended specifications;
(g) Check and maintain access to the station;
(h) Record, in note form, all of the above activities;
(i) Comment on changes in land use or vegetation;
(j) Clear debris and overgrowth from all parts of the installation.

Streamflow collection sites:
(a) Check the bank stability, as necessary;
(b) Check the level and condition of gauge boards, as necessary;
(c) Check and service the flow-measuring devices (cableways, etc.), as necessary;
(d) Check and repair control structures, as necessary;
(e) Regularly survey cross-sections and take photographs of major station changes after events or with vegetation or land-use changes;
(f) Record, in note form, all of the above activities and their results;
(g) Inspect the area around or upstream of the site, and record any significant land-use or other changes in related hydrological characteristics, such as ice.

Further details are found in the *Manual on Stream Gauging* (WMO-No. 519).

Flood gauging cannot be programmed as part of a routine inspection trip because of the unpredictable nature of floods. A flood action plan should be established prior to the beginning of the storm season and should include priority sites and types of data required. If flood gaugings are required at a site, the preparations must be made during the preceding dry season so that all is ready during the annual flood season. Additional measures may be required if severe flooding is likely.

Preparations include:
(a) Upgrade site access (helipad, if necessary);
(b) Equip a temporary campsite with provisions;
(c) Store and check gauging equipment;
(d) Flood-proof instrumentation such as stage recorders.

Following the recession of flood waters, particular attention is required to ensure the safety and security of the data-collection site and to restore normal operation of on-site instrumentation. In some cases redesign and reconstruction of the site will be required. This work should take into account information obtained as a result of the flood.

2.5.5 Observations

At all data-collection sites a value must first be sensed, then encoded or recorded, and finally transmitted. Examples of the components of data collection are displayed in Table I.2.9.

2.5.5.1 Manual stations

At the very minimum, observers should be equipped with field notebooks and/or station journals in which the original observations are recorded as they are taken. Forms should also be provided to permit the observer to report observations daily, weekly, fortnightly, or monthly, as required. The field notebook or station journal should be retained by the observer in case the report is lost in transit.

The report forms should be designed to permit easy copying of the results from the field notebook or station journal. A good approach is to have the report form identical to a page in the notebook or journal. At least, the various elements should be in the same columns or rows in both. Space should be allowed in the journal and, perhaps, in the report form for any conversions or corrections that may have to be applied to the original readings.

Alternatively, an observation notebook with carbon paper between successive sheets will permit easy preparation of an original form for dispatch to the central office and a copy for the local station record. This is not a satisfactory procedure where the notebook is to be carried into the field as moisture can easily make the entries illegible. The report forms may also be coding forms suitable for direct conversion to computer medium.

The value of data can be greatly enhanced – or devalued – by the standard of the accompanying documentation. Observers should be encouraged to comment on any external influences that may affect observations, whether they be related to equipment, exposure, or short-term influence. In addition, input formats and forms should be flexible enough both to allow comments to be appended and for these comments to be accessible with the final data. It is important that published comments be expressed in standard terminology, and it is preferable that correct vocabulary be employed in the field report.

There is also reason for setting up the processing system so that quality coding or tagging is carried out as the observations are made. This is particularly applicable to manual observations because it encourages the making of judgements while the conditions are being observed. Data from field measurement books may be processed using optical readers or portable field computers that will allow the direct input of observations into computer storage. Such devices allow for reduced data transfer errors and automatic data quality checks.

Field observations that may assist in interpreting water quality should be entered on the report. These observations may include unusual colour or odour of the water, excessive algal growth, oil slicks, surface films, or heavy fish kills. Such observations may prompt the field investigator to take additional observation-based samples, in addition to those required by the routine schedule. The types of samples and their preservation should be consistent with the types of analysis that the investigator thinks is warranted by the prevailing conditions. If additional samples are collected at sites other than the established station, the description of their locations should be recorded accurately. This kind of information and the additional samples may prove very useful in the interpretive phase of the study.

Table I.2.9. The components of data collection

Data collection		
Data capture		*Transmission*
Sensing	*Recording*	
1. Visual Water-level gauge, land use, site description, soil texture, etc.	1. Field notebook Text descriptions and element or parameter values	1. Manual Field observers Postal services Telephone
2. Mechanical Raingauge, thermometer, current meter, soil penetrometer, water level gauge	2. Field data sheet Purpose designed for particular text decriptions and element or parameter values May be pre-coded for subsequent computer input purposes	2. Automatic (Telemetry) Telephone Dedicated landline Radio Satellite Internet Mobile phone networks
3. Electrical Thermistor, radiometer, pressure transducer, conductivity probe, encoder	3. Charts Strip charts with element value continuously recorded by pen tracing	
	4. Computer compatible media (a) Manually recorded Mark sense forms Multiple choice forms (b) Automatically recorded Solid state memory	

Note: The table applies to elements or parameters observed in the field. There are notable groups of data, for example, in soils and water quality, where laboratory analysis or physical samples are performed. Here the data-collection system almost invariably is:
(a) Mechanical sampling
(b) Notebook/data sheet field entries.

2.5.5.2 Recording stations

At automatic recording stations, observations are recorded in digital or graphical form. However, the following observations should be recorded at the time of any visits for data retrieval or station maintenance:

(a) Site identification number;
(b) Observations from independent sources at the time of collection, for example, gauge boards and storage rainfall gauges;
(c) Specific comments relating to the recording device, including its status, current observation and time.

Each inspection should be recorded by completing a station-inspection sheet. Data may be recorded in solid-state memory or perforated tape. Final extraction of observations from the recorded data may be performed at computing facilities when removable memory of perforated tape has been used as the recording medium. However, portable computers may be used to extract data directly from data loggers and to verify the data before leaving the station. Field verification allows any necessary repairs or other changes to be made before leaving the site.

Data loggers record data at specific time intervals (as programmed by the user). Intelligent loggers will also allow for data compaction and variability of observation times. In the case of the observation of multiparameters, the coordination of observations can also be performed by the intelligent field logger. For example, rainfall data can be recorded at a five-minute interval or at every tip of a bucket, for stage data when the level alters by more than 1 cm, and water-quality parameters when stream height alters by 10 cm and/or on a 24-hour basis.

With graphical recorders, observations are collected continuously and processing of the data in the office is required. Comments should be written on the chart or noted on the inspection sheet if any errors are detected. As with digital recorders, independent field observations should be made and recorded during each site visit.

After a station has been in operation for a reasonable period, the frequency and timing of inspections should be re-assessed in the light of the capabilities of the instrumentation and the requirements for data at that site. In some cases, consideration should be given to the real-time collection of data via various communications options as a cheaper method of data collection than regular site visits (2.5.6).

2.5.5.3 Real-time reporting

There are many recording and non-recording stations from which real-time data are required, for example, in the operation of reservoirs, flood-warning and forecasting situations, and in some instances as a cost-effective method of data collection.

Real-time data collected by field observers must be reported using a transmission facility, such as a radio or the public telephone system, to the agency. Similarly, recording stations must report via some transmission facility. Recording devices may have the advantage of being able both to transmit data at prescribed intervals/parameter changes and be interrogated by the collecting agency to determine the current situation or reset observation intervals. Data loggers may also provide information on the current available storage capacity of the logger and the condition of the available power supply. Automated quality-control processes can be developed in these situations.

2.5.5.4 Instructions for observers

Clearly written instructions must be provided to all observers. These should contain guidance and directions on the following matters:

(a) A brief description of instruments, with diagrams;
(b) Routine care and maintenance of instruments and actions to be taken in the event of serious breakage or malfunctioning;
(c) Procedures for taking observations;
(d) Times of routine observations;
(e) Criteria for the beginning, ending and frequency of special non-routine observations, for example, river-stage observations while water level is above a predetermined height;
(f) Procedures for making time checks and putting check observations on charts at stations with recording instruments;
(g) Completion of field notebooks or station journals;
(h) Completion of report forms, including methods of calculating means and totals with appropriate examples;
(i) Sending of reports to the central office;
(j) Special routines for real-time stations.

Such written instructions should be supplemented by oral instructions by the inspector to the observer at the time of installation of instruments and at regular intervals thereafter.

The instructions should emphasize the importance of regular observations with perhaps a brief account of how the observed data are used in water resources development, hydrological forecasting, or flood-control studies. Any special observations that may be required during special periods, for example, during floods, or any special reports that are to be filed, should be specifically discussed. Observers should be urged not to forget to fill in the spaces for station names, dates and their signature. The necessity of reporting immediately any instrument failure or significant modification of the observing site should be emphasized.

Observers at stations equipped with automatic recording instruments must be provided with instructions on the method of verifying the operation of digital recorders, changing charts and taking check observations. These instructions must stress the importance of annotating the chart with all information that might be required for later processing. This would include station identification, time on, time off, check-gauge readings and any other entries that would make the record more easily interpreted at a later time.

At stations with full-time personnel, the staff should be sufficiently well trained to abstract data from recording instruments. For such stations, carefully worded instructions on the method of abstracting data and on the completion of report forms must be provided. However, at many ordinary stations, where observers may not be thoroughly trained, it may be undesirable to require observers to undertake the relatively complex job of data abstraction. In such cases, digital or graphical records should be forwarded to a central office for processing of the data.

2.5.6 Transmission systems

2.5.6.1 General

During recent years, the demands from users of hydrological data have become more and more complex; therefore, systems that include automatic transmission of hydrological observations have been incorporated into national networks. This has also led to the need for developing codes to facilitate the formatting of observations for the transmission and dissemination of forecasts. Hydrological codes are discussed in 2.3.2. The following describes different possibilities for transmission systems:

(a) Manual – The observer at the station mails data or initiates radio or telephone calls to the central office on pre-arranged criteria;
(b) Manual/semi-automatic – The central office manually interrogates the remote automatic station by telephone, Internet, radio or radio telephone or satellite, and receives single discrete values as often as interrogated. It is possible to have automatic telephone-dialing equipment in the central office that can make calls in series;
(c) Automatic timed – Automatic equipment at stations is programmed to initiate transmission of a single, instantaneous observation and/or past observations held in a storage register;
(d) Automatic event indicator – The station transmits automatically, by radio, telephone, Internet or satellite, a specified unit of change of a variable, for example, each centimetre change in the stage of a river;
(e) Automatic – Data are transmitted by the station and recorded at the central office on a continuous basis.

2.5.6.2 Transmission links

The possible choices of transmission links include:

(a) Dedicated land-lines – These are used where relatively short distances are involved and commercial lines are not readily available;
(b) Commercial telephone and telegraph lines – Telephone and telegraph systems can be used whenever feasible. Equipment that permits unattended reception of observations at the central office is available. Measurements and commands can be transmitted to and from the remote site;
(c) Commercial cellular telephone networks – The ever growing coverage of these networks, together with better and more reliable equipment, make them an interesting and less expensive option for moving data from a site and into the central office. The combination of reliability and low cost makes it more realistic to collect data from stations with no real-time interest, from sites previously considered as somewhat remote, to be transmitted using commercial facilities. Cellular systems can be used in the same way as standard telephone lines and may continue to operate during an extreme event when telephone lines fail;
(d) Direct radio links – These must be used when requirements cannot be met by those facilities provided by landlines, or when distances or natural obstacles prevent the economic installation of wires. Distances of several to hundreds of kilometres may be spanned by radio transmitters, depending upon the carrier frequency and the transmitter power. At the higher frequencies, the transmitter and receiver must have a clear line-of-sight transmission path. This limits the range without repeater

stations to about 50 km. In all cases, the installation and operation of radio transmission links are subject to national and international regulations;

(e) Satellite links – Data transmission using satellites can take place in two ways: transmission of data, as observed by sensors in the satellite (such as imagery) or the use of the satellite to relay data observed at remote ground stations to central receiving locations. At the present time, the science of observation and transmission or retransmission from satellites is developing rapidly. The data involved are available either directly from the spacecraft or through central data banks;

(f) The Internet – Internet Protocol communication in various forms, including the use of mobile phone networks, makes this an interesting and less expensive way to send data, especially if there is much data to transfer or continuous transfer is wanted. Internet communication works on a number of different physical communication paths, including both mobile and ordinary telephone networks. This makes it more reliable. In systems with a large number of sites, it also makes the retrieval time shorter and the communication system in the main office much easier.

2.5.6.3 Factors affecting the choice of transmission systems

When considering the possibility of including automatic transmission of data in any measuring system, consideration should be given to the following:

(a) Speed with which data are required. This depends upon the following factors:
   (i) The speed with which changes in the measured variable take place;
   (ii) The time between the observation and receipt of the data by conventional means, versus automatic transmission systems;
   (iii) The urgency of having this information available for warnings or forecasts;
   (iv) The benefits of forecasts from telemetered data and economic losses due to lack or delay of forecasts;
   (v) The advantages of radio and satellite transmission versus landlines in times of storms and floods when these disasters can destroy the more conventional means of telecommunications at the time that the information is most urgently needed;

(b) Accessibility of the measurement sites for quality control and maintenance;

(c) Reliability of the recording device. When local climatic conditions are rigorous, the operation of on-site mechanical equipment is difficult. Under these situations, it may be more reliable to transmit data electronically to a central climate-controlled office. This system also permits a continuous check of the operation of the sensors;

(d) Staffing for operational, maintenance and logistic problems. It is important for these aspects to be considered in the planning process and to recognize that each individual project will have its own particularities. Careful attention should be given to the costs and benefits of all the alternatives before any final decision is made. When designing a system for the automatic transmission of data, the main components to consider for staffing purposes are:
   (i) Sensors and encoding equipment;
   (ii) The transmission links;
   (iii) Receiving and decoding equipment.

It is necessary to consider these components jointly in the design stage. This is essential because the special characteristics of any one component can have serious consequences on decisions regarding the others. If the ultimate use of the data transmission system is intended for forecasting, then sensing, transmitting and receiving hydrometeorological data is an essential but insufficient component of the forecast system. A forecast centre having personnel who are well-trained in preparing forecasts and warnings, and in notifying persons at risk is also fundamental (United Nations, 2004).

2.5.7 Water-quality monitoring

Chapter 7 provides details of instrumentation and field practices for the collection of water-quality data. The sampling locations, the sampling times, the parameter identifications and the corresponding values must be recorded and coherence must be maintained throughout the handling of the data. If any one of these essential items is lacking, then the whole effort is wasted.

2.5.7.1 Station identification

The importance of an accurate written description of each station location and the conditions under which the samples are collected are discussed in detail in 2.5.2.2.

2.5.7.2 Field sheets for water-quality monitoring

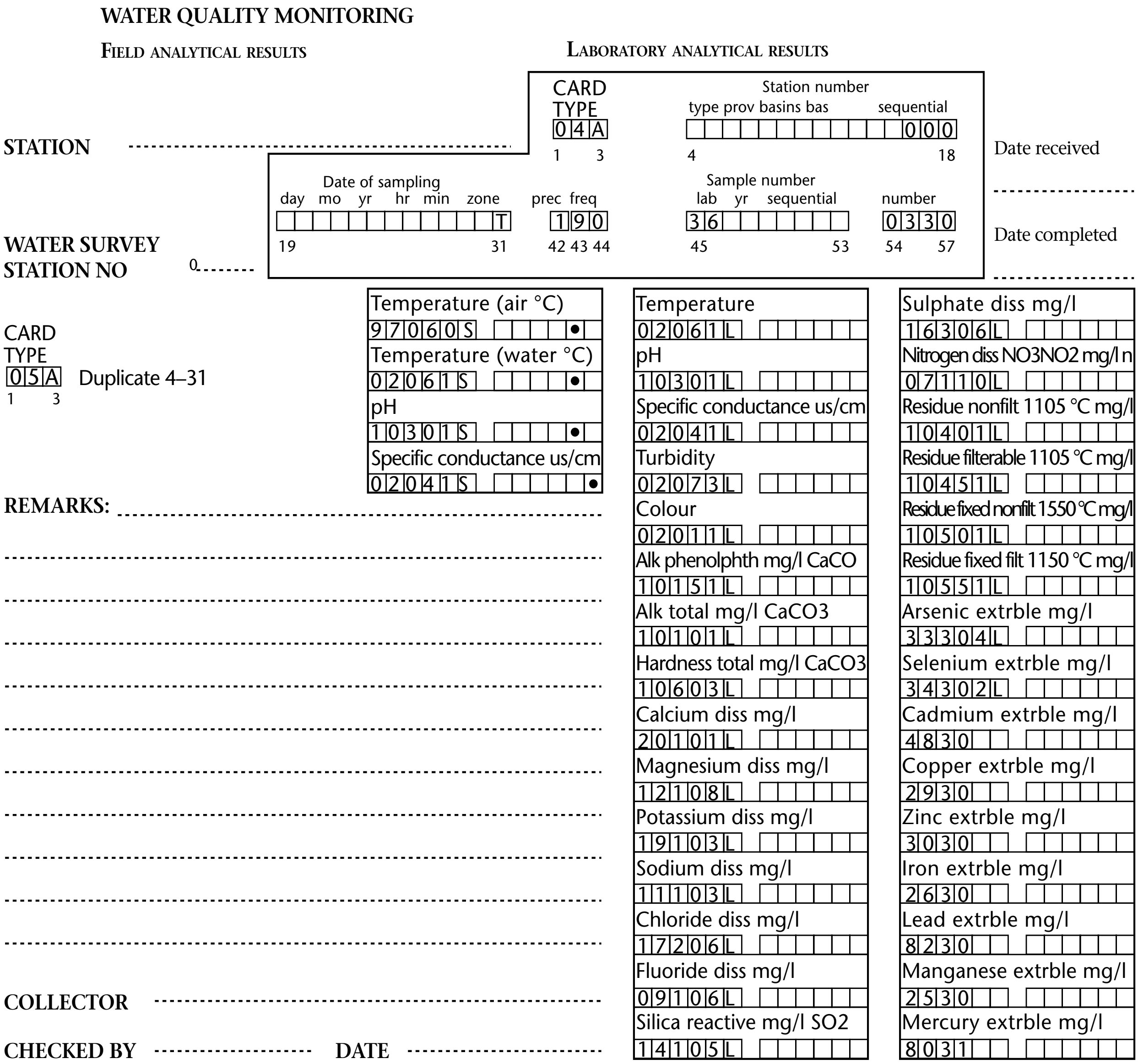
Perhaps one of the most important steps in a sampling programme is the recording on the field sheets of observations, sampling date, time, location and the measurements made. All field records must be completed before leaving a station. Additional instructions are contained in 2.5.5.

Two examples of a systematic format for recording field analyses and observations are provided in Figures I.2.13 and I.2.14. The formats shown in these figures are appropriate for those personnel that use computer systems for storing their results. The format of Figure I.2.13 can be used by anyone collecting water-quality data. Both formats can be adapted to fit situations specific to a particular need. The following information is usually recorded:

(a) Sampling site and date;
(b) Field-measured parameters;
(c) Instrument calibration;
(d) Sampling apparatus used and procedures;
(e) Quality control measures used;
(f) General remarks and field observations.

2.5.7.3 Transportation of water-quality samples

Once collected, some water samples must be transported to the laboratory. The mode of transportation will depend on the geographic location and the maximum permissible time lapse before analysis for each constituent. The field investigator is responsible for delivering the samples to the airline, bus, train or postal terminal on schedule so that there will be minimal delay in sample transport. Logistics for sample transport and storage should be determined before fieldwork is initiated.



WATER QUALITY MONITORING

FIELD ANALYTICAL RESULTS

LABORATORY ANALYTICAL RESULTS

CARD TYPE 0 4 A (1 3) — Station number: type prov basins bas sequential 0 0 0 (4 18)

STATION

Date received

Date of sampling: day mo yr hr min zone T (19 31) — prec freq 1 9 0 (42 43 44) — Sample number: lab yr sequential 3 6 (45 53) — number 0 3 3 0 (54 57)

Date completed

WATER SURVEY STATION NO 0

CARD TYPE 0 5 A (1 3) Duplicate 4–31

Temperature (air °C) 9 7 0 6 0 S •	Temperature 0 2 0 6 1 L	Sulphate diss mg/l 1 6 3 0 6 L
Temperature (water °C) 0 2 0 6 1 S •	pH 1 0 3 0 1 L	Nitrogen diss NO3NO2 mg/l n 0 7 1 1 0 L
pH 1 0 3 0 1 S •	Specific conductance us/cm 0 2 0 4 1 L	Residue nonfilt 1105 °C mg/l 1 0 4 0 1 L
Specific conductance us/cm 0 2 0 4 1 S •	Turbidity 0 2 0 7 3 L	Residue filterable 1105 °C mg/l 1 0 4 5 1 L
	Colour 0 2 0 1 1 L	Residue fixed nonfilt 1550 °C mg/l 1 0 5 0 1 L
	Alk phenolphth mg/l CaCO 1 0 1 5 1 L	Residue fixed filt 1150 °C mg/l 1 0 5 5 1 L
	Alk total mg/l CaCO3 1 0 1 0 1 L	Arsenic extrble mg/l 3 3 3 0 4 L
	Hardness total mg/l CaCO3 1 0 6 0 3 L	Selenium extrble mg/l 3 4 3 0 2 L
	Calcium diss mg/l 2 0 1 0 1 L	Cadmium extrble mg/l 4 8 3 0
	Magnesium diss mg/l 1 2 1 0 8 L	Copper extrble mg/l 2 9 3 0
	Potassium diss mg/l 1 9 1 0 3 L	Zinc extrble mg/l 3 0 3 0
	Sodium diss mg/l 1 1 1 0 3 L	Iron extrble mg/l 2 6 3 0
	Chloride diss mg/l 1 7 2 0 6 L	Lead extrble mg/l 8 2 3 0
	Fluoride diss mg/l 0 9 1 0 6 L	Manganese extrble mg/l 2 5 3 0
	Silica reactive mg/l SO2 1 4 1 0 5 L	Mercury extrble mg/l 8 0 3 1

REMARKS:

COLLECTOR

CHECKED BY DATE

Figure I.2.13. Field sheet for use with NAQUADAT or similar computer system

STATION NO. ______________________________
DESCRIPTION ______________________________
____
DATE OF SAMPLING DY __________ MO __________ YR __________
TIME OF SAMPLING HR __________ MI __________ TIME ZONE __________
SAMPLED BY ______________________________
FIELD MEASURED PARAMETERS
Water temp. °C __________ Air temp. °C __________
pH ______ Specific cond. ______ Diss. oxygen ______ Turb. ______
Depth of water __________ Depth at which sample taken __________
Ice thickness ______________________________
Other ______________________________
Remarks ______________________________
____
INSTRUMENT CALIBRATION
Diss. oxygen meter model __________ Winkler calibration __________ mg/L
Meter reading before adjustment ______________________________
Conductivity meter model ______________________________
pH meter model __________ Calibration butters used __________
Remarks ______________________________
____
WATER QUANTITY MEASUREMENT DATA
Location description ______________________________
____
Description of gauge ______________________________
____
Stage height ______________________________
Time ______________________________

Figure I.2.14. General format for a field-sampling sheet

2.5.7.4 Field quality assurance in water-quality monitoring

A field quality assurance programme is a systematic process that, together with the laboratory and data-storage quality assurance programmes, ensures a specific degree of confidence in the data. A field quality assurance programme involves a series of steps. All equipment should be kept clean and in good working condition, with records kept of calibrations and preventive maintenance. Standardized and approved methodologies, such as those recommended in this Guide, should be used by field personnel.

The quality of data generated in a laboratory depends on the integrity of the samples that arrive at the laboratory. Consequently, the field investigator must take the necessary precautions to protect samples from contamination and deterioration. Further details on field quality assurance are available in Chapter 7 of the present Guide; ISO Standards (ISO 5667–14:1998 Water quality-Sampling – Part 14: Guidance on quality assurance of environmental water sampling and handling), in the *Water Quality Monitoring: A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes* (UNEP/WHO, 1996); and the *Manual on Water Quality Monitoring: Planning and Implementation of Sampling and Field Testing* (WMO, 1988).

2.5.8 Special data collection

2.5.8.1 Requirement

Data concerning severe storms and floods are very important in determining design criteria for many types of hydraulic structures. In general, regular observation networks do not provide enough detailed information on storm-rainfall distribution, or on flood-peak discharges of tributary streams. In addition, during severe floods, permanent stream-gauge installations are sometimes overtopped or washed away and the record is lost. For these reasons, very valuable information can be obtained by a field survey crew in the area of a storm flood immediately following a severe occurrence. In addition, data from instruments, such as weather radar, are often valuable in hydrological studies (3.7).

2.5.8.2 Bucket surveys of storm rainfall

Measurements of rainfall from private, non-standard raingauges, and estimates that can be made from various receptacles, such as pails, troughs and barrels (provided these can be verified to have been empty prior to the storm), can be used to augment rainfall data from the regular observing network. Eyewitness reports can be obtained of beginning and ending times of rainfall and of periods of very heavy rain. Care must be taken in interpretation of bucket-survey data, and where discrepancies exist between data from a bucket survey and the regular observation network. Greater weight should usually be given to the latter.

2.5.8.3 Weather-radar and satellite data

Data from weather radars and satellites are valuable in determining the intensity and areal distribution of rainfall and beginning and ending times of precipitation over a specific river basin. For record purposes, these data can be collected on photographic film or in digital form by a computer linked to the radar. These digitized data can be readily transmitted to forecast offices over computer networks.

2.5.8.4 Extreme river stages and discharges

Extreme events during floods and droughts should be documented at both regular gauging stations and at non-gauged locations.

High-water marks along rivers are useful in delineating flooded areas on maps, in the design of structures such as highway bridges, and for estimation of flood slopes. These marks, if taken carefully, may also be used with other data to compute the peak discharge of the stream by indirect methods (5.3.5).

Field surveys to measure minimum streamflow at non-gauged locations provide valuable data at a very economical cost. These measured discharges can be correlated with the simultaneous discharges at regular gauging stations to determine the low-flow characteristics at the ungauged sites.

2.5.8.5 Video imagery techniques

A video camera installation can provide valuable information about the conditions at a gauging site. The extent of ice cover, periods of backwater due to ice, etc., can be documented by a camera. This technique can also be used for remotely monitoring potential hazards, for example, risks due to avalanches.

Recently, video imagery-based approaches have been used to measure discharge by estimating surface velocities using particle image velocimetry methods The video data can be recorded on site, or, if real-time information is required, readily reported via some transmission facility.

2.6 MEASUREMENT OF PHYSIOGRAPHIC CHARACTERISTICS

2.6.1 General

The concepts discussed in this section cover two quite different physiographic characteristics: the location of the feature(s) under study, and their physical response to atmospheric events. By locating these features, it is possible not only to catalogue them, but also to determine their spatial distribution and the climate zone to which they belong.

The features themselves can be examined in terms of points, lines, areas or volumes depending on the relationship between a particular characteristic and the hydrological regime. For example, streamflow results from the transformation of climatic events (rainfall, snow melt) by the physical complex that comprises a drainage basin. The basin location partially determines the climatic characteristics, which are responsible for meteorological events that drive the hydrology. However, the basin's physical characteristics not only control the hydrological response to the meteorological events, but some characteristics, for example, orography and aspect, can also be causal factors in the determination of the basin's climate.

Physiographic characteristics are now commonly examined as layers of information within contemporary GIS. The physical response of a watershed to meteorological events can be analysed using hydrological and hydraulic models as well. The fundamental procedures presented in this section form the basis for computer-assisted data assembly and analysis.

2.6.2 Reference systems and data frameworks

Physiographic characteristics are but one component of geospatial information; that is, information pertaining to the character and location of natural and cultural resources and their relation to human activity. This information has become so important that the concepts of national and international spatial data infrastructure and framework data have been developed. Spatial data infrastructure can be considered as the technology, policies, criteria, standards and people necessary to enable geospatial data sharing throughout all levels of government, the private and non-profit sectors, and academia. It provides a base or structure of practices and relationships among data producers and users that facilitates data sharing and use. Framework data can be considered as a set of continuous and fully integrated geospatial data that provides context and reference information for the country or region. In general, this will consist of alignment data such as geodetic control, data on land features and form such as physiographic data, and conceptual data such as government units. A rigorous national data framework facilitates information exchange and significantly reduces duplication of effort. Framework data that will be of interest to hydrological analysis include geodetic control, elevation, orthoimagery, hydrography, transportation, government units and cadastral information (National Research Council, 1995).

Geodetic control is defined by using the international system of meridians and parallels divided into 360 degrees, with the zero meridian passing through Greenwich. This system is the most widely used. Its only disadvantage is that a degree in longitude varies from 111.111 km at the Equator to 0 at the Pole and represents 78.567 km at a latitude of 45° (a degree in latitude always measures 111.111 km). Local systems and other modes of projection are also in use, for example, the Lambert system. However, these cannot be recommended in an international guide. Furthermore, algorithms for converting geographic coordinates to local reference systems when this may be required are readily available.

Elevation or altitude is provided in relation to a given level or reference plane. While local reference data are sometimes used, until relatively recently mean sea level was the most commonly used vertical data. The widespread use of global positioning system observations led to the adoption of geocentric vertical (and horizontal) data in accordance with the world geodetic system, in preference to those based on mean sea level. The reference ellipsoid, WGS-84, or a national geocentric variation is therefore the preferred vertical reference. The fundamental requirement in any use of a coordinate system is that the data used must be specified.

The topography of a river basin may be represented in two different ways: as a digital elevation model or as a triangulated irregular network (TIN). The digital elevation model is a grid of elevation values that has regular spacing while TIN is a series of points linked into triangular surfaces that approximate the surface. The spacing of points in TIN are non-uniform, which allows points to be located on critical terrain features, roads or river banks. The accuracy of such digital terrain models depends on the source of the data, the point density and distribution, and other related data used in their development. Conventional contour maps may be prepared from a digital elevation model or TIN.

Orthophotos are images of the landscape from which features can be referenced to one another. They are digital images produced by processing aerial photography to geodetic control elevation data to remove all sources of distortion. The image has the properties of scale and accuracy associated with a map. Such images can be derived using airborne or satellite sensors.

The basic elements used in estimating physiographic parameters are rarely measured directly by the hydrologist, who essentially works with global positioning system data, orthophotos, maps, aerial photographs and satellite imagery. Therefore, the accuracy of the evaluation depends upon the accuracy of source materials.

2.6.3 Point measurements

The geometric point is defined here as a unique location on a line or within an area or volume. A point may be a physical element, such as the location of a measuring instrument or the outlet of a basin. It can also be an element of an area (plot of land) on which a given characteristic or set of characteristics is to be defined or measured. The physiographic characteristics attributed to a point may be simple or complex. An example of a simple characteristic of a point is its elevation, which is one of its unique identifiers in three-dimensional space. A more complex characteristic might be a description of the soil profile that underlies the point.

Applications of remote-sensing techniques, starting with aerial photography, has had the effect of expanding the notion of a point to an area (pixel), which may measure up to several square kilometres. Within their limits of accuracy, available techniques may not be able to distinguish between two points (for example, an instrument's lack of resolution), and a pixel might be taken to be a point.

The horizontal location of a point, that is, its position on the globe, is determined by a selected system of coordinates (2.6.2), which falls within the scope of geodesy and topography. A universal system has been invented to make the coding of a point in a catalogue explicit by indicating its geographical position. This is the GEOREP squaring system (UNESCO, 1974) for spatial representation of linear features. Other systems may locate points by their linear distances along a stream from a given origin, for example, mouth or confluence.

The physiographic description of a point covers its geometric properties (form, relief, slope, etc.) and its permanent physical properties (permeability, nature of rocks, soil structure, land-use type, etc.). The former are limited to the local slope, while the latter comprise a whole range of possible physical properties, expressed in scalar form for a point on a horizontal surface or in vectorial form for a profile, for example, geological core.

2.6.4 Linear measurements

Any physiographic element is linear if it can be represented by a line on a map or in space. In hydrology, three types of linear elements are common:

(a) Boundaries;
(b) Isopleths of a permanent feature, for example, contours;
(c) Thalwegs.

The first two types are linked to areal aspects, which will be examined later.

The thalweg is itself to be considered not only as represented in horizontal projection and longitudinal profile, but also by the way in which it combines with other thalwegs to form a drainage network, which has its own physiographic characteristics. Some drainage network characteristics are linear, for example, the bifurcation ratio, while others are areal in nature, such as the drainage density.

2.6.4.1 The stream

A stream in horizontal projection may be represented, if the scale of the diagram is suitable, by two lines representing its banks. From these two lines, an axis can be drawn equidistant to the two banks. The axis may also be defined as the line joining the lowest points on successive cross-sections. In fact, these elements, the visible banks and the lowest points, are not always very clear, and the map scale does not always permit the banks to be featured properly. Mapping, thus, is reduced to representing a stream by a line.

Lengths along a river are measured by following this line and by using a curvometer. The accuracy of the determination depends on the map's scale and quality, as well as on the curvometer's error, which should not exceed six per cent for a distance on the map of 10 cm or 4 per cent for 100 cm and 2 per cent beyond. Many hydrological features can be derived directly from the orthoimagery or digital terrain data with the aid of GIS (2.6.7).

The axis of a stream is rarely straight. When it comprises quasi-periodic bends, each half-period is called a meander. The properties and dimensions of meanders have been thoroughly studied by geographers and specialists in river hydraulics.

2.6.4.2 The drainage network

In a basin, streams are organized to form a drainage network. In a network, all streams are not the same size, and several systems have been proposed for classifying them. Several stream classification systems are in use in various countries and current GIS provide for automatic stream classification according to schemes devised by Horton, Schumm, Stahler, Shreve and others. The best known schemes is Horton's, in which any elementary stream is said to be of order 1, any stream with a tributary of order 1 is said to be of order 2, and any stream with a tributary of order x is said to be of order $x + 1$. At a confluence, any doubt is removed by giving the higher order to the longest of the tributaries forming it (Figure I.2.15) (Dubreuil, 1966). This introduces some inaccuracy that was avoided by Schumm by systematically giving order x to the reaches formed by two tributaries of order $x – 1$ (Figure I.2.16). The main source of error in such evaluations is to be found in the mapping of the streams, where the definition of the smallest streams is often rather subjective.

Of the linear characteristics of the drainage network that are measurable on a map, the confluence ratio R_c and the length ratio R_l are based on Horton's laws and have been verified for Horton's classification. Given that N_x is the number of streams of order x, and $lm_x=\sum l_x/N_x$ is the mean length of the streams of order x, these laws are expressed by the following relationships:

$$N_x = R_c * N_{x+1} \tag{2.9}$$

and

$$lm_x = R_l * lm_{x-1} \tag{2.10}$$

which form geometric progressions and may be written as follows:

$$N_x = N_1 * R_c^{1-x} \tag{2.11}$$

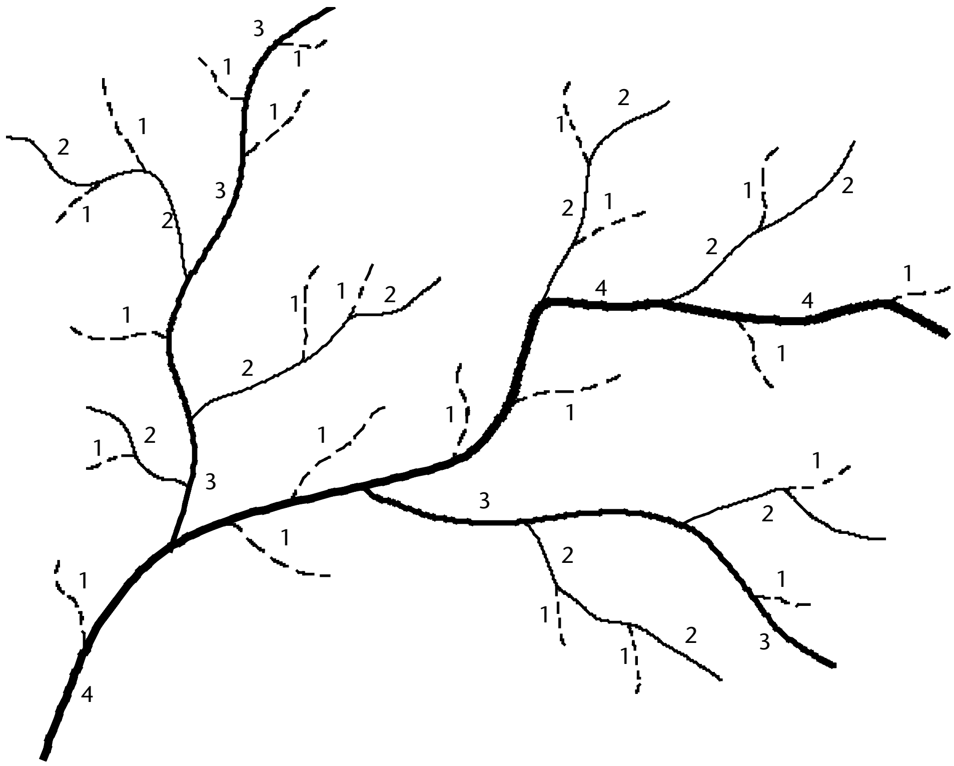


Figure I.2.15. Horton's classification

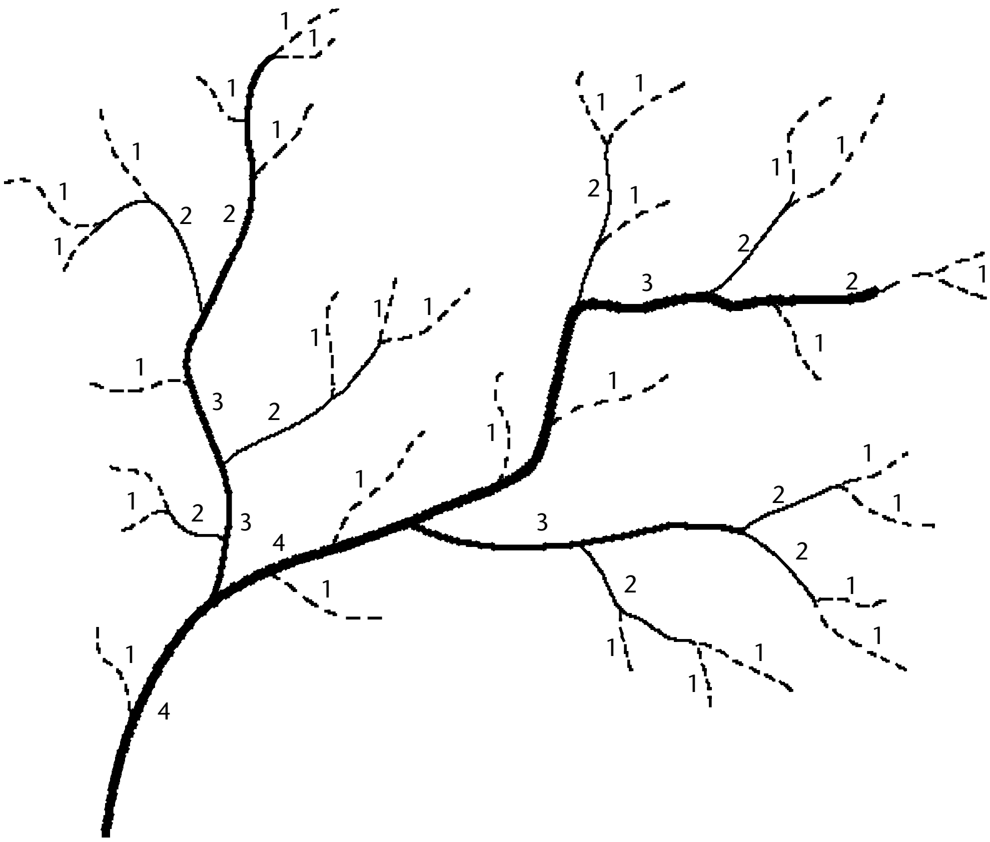


Figure I.2.16. Schumm's classification

and

$$lm_x = R_l^{x-1} * lm \qquad (2.12)$$

where R_c and R_l are calculated as the slopes of the straight lines adjusted to the graph points (log N_x, x) and (log lm_x, x) and x is the basin order.

2.6.4.3 Stream profile

The stream profile is the variation in elevation of the points of the stream thalweg as a function of their distance from the origin, which is generally taken as the confluence of the stream with a larger stream or as its mouth. On such a profile, a certain number of topographical features are to be found, such as high points (thresholds), hollows between two thresholds (pools), rapids, waterfalls and changes of slope that frequently mark the boundary between two reaches with different geologic controls (Figure I.2.17).

The average slope of a whole stream is the difference in elevation between its highest point and its confluence or mouth divided by its total length. This notion is simple, but not very useful. On the other hand, knowledge of the slopes of the successive stream reaches is essential for most runoff and hydraulic models.

The profiles of the main stream and of various tributaries in the same basin can be represented on the same diagram. Figure I.2.18 shows examples of stream profiles of the Niger river at Koulikoro and of its main tributaries and sub-tributaries. Such a diagram gives a synthesized view of the variation in slope of the drainage network's elements.

2.6.4.4 Cross-section

The profile of the valley taken perpendicular to a stream's axis is called a cross-section, and a series of these is valuable information for the development of streamflow models. Cross-sections are used in several types of calculations, and the way in which they are established may depend on the use to which they will be put.

An important particular case is the calculation of flow for a discharge measurement, in which elevation is expressed as a depth and is obtained by sounding (5.3). Cross-sections are usually obtained by making normal topographical measurements during the lowest flows.

2.6.4.5 Physical characteristics

The type of material in the stream bed (particularly its cohesiveness), the type and amount of vegetation in and along the stream, and the roughness of the bed, which depends on the longitudinal and transverse distributions of the former, comprise the primary physical characteristics of a stream. Roughness is incorporated in the flow calculations

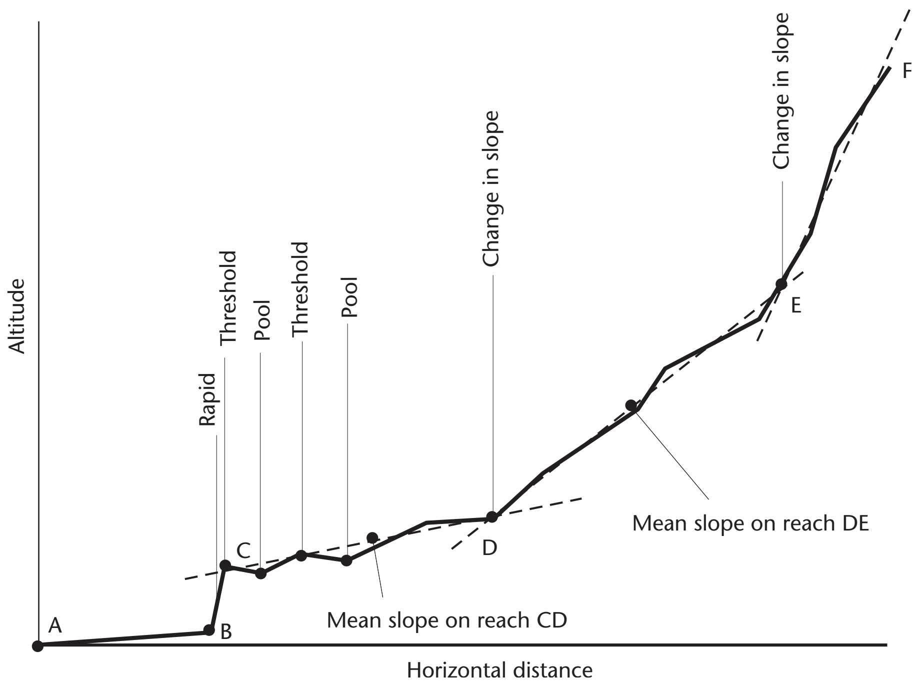


Figure I.2.17. Stream profile

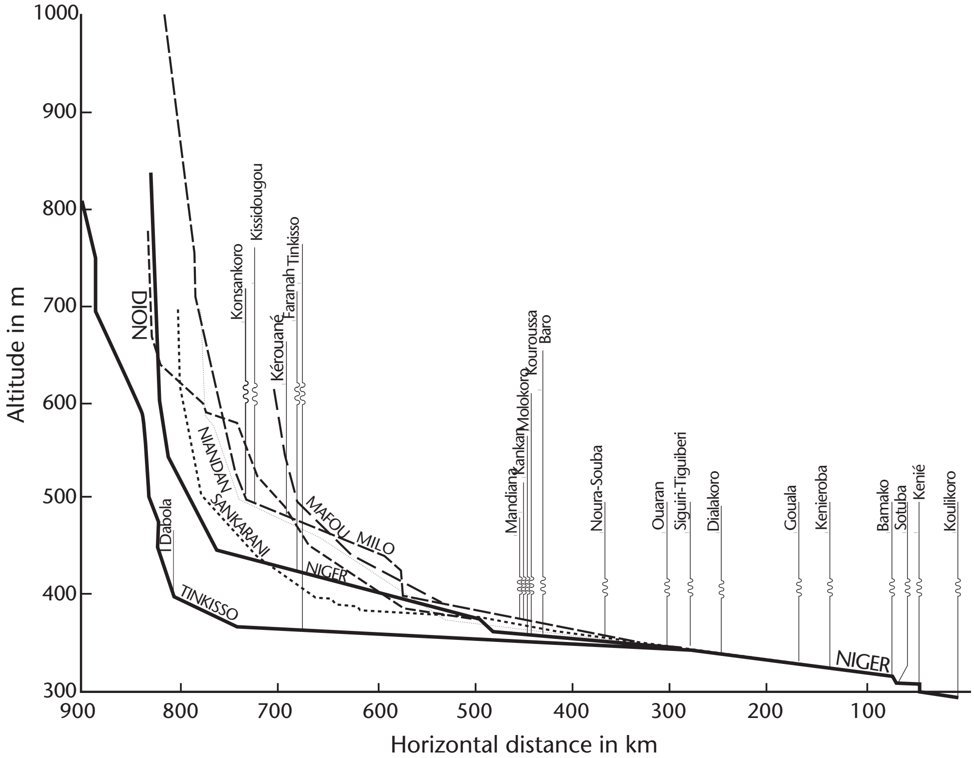


Figure I.2.18. Profile of the Niger river and its tributaries

by the indirect method (5.3.5) and in runoff models (Volume II, Chapter 6).

2.6.5 Area measurements

2.6.5.1 The basin

The basin is defined as the area that receives precipitation and, after hydrological processes resulting in losses and delays, leads it to an outflow point. The watershed boundary, the basin's perimeter, is such that any precipitation falling within it is directed towards the outflow, whereas any precipitation falling outside drains to a different basin and outflow. In some cases, it may not be easy to determine the basin boundary, for example, when the head of the main stream is formed in a very flat-bottomed valley or a marshland. The watershed is usually defined by using contour maps or aerial photographs.

The basin perimeter is measured in a GIS (2.6.7) or with a curvometer. The measured perimeter is a function of the scale and accuracy of the maps or photographs, the quality of the curvometer, and the care taken in its use (Figure I.2.19). The ultimate use that will be made of the measurement should determine the accuracy to which it is measured.

The basin area is determined in a GIS or measured by planimetry by following the boundaries established as described above.

The basin's shape is characterized by comparing its perimeter with that of a circle having the same area. If A is the basin area and P its perimeter, both measured according to the above rules and expressed in compatible units, then the ratio of the

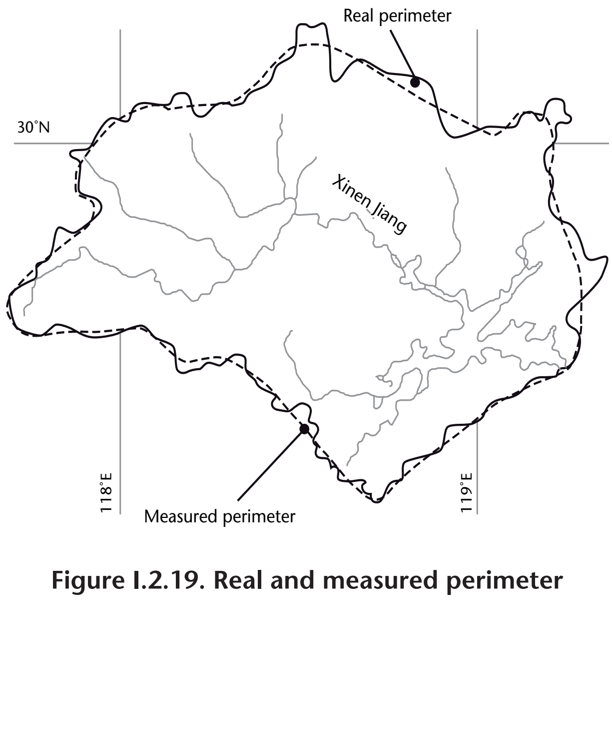


Figure I.2.19. Real and measured perimeter

two perimeters is called the Gravelius coefficient of compactness, which is given by:

$$C = 0.282\ P\ A^{1/2} \tag{2.13}$$

The notion of an equivalent rectangle is also linked to the basin's shape, and permits the definition of a particular slope index. The equivalent rectangle has the same area and the same Gravelius coefficient as the basin. The length of this rectangle is:

$$L = A^{1/2} \frac{C}{1.128} \left[1 + \sqrt{1 - 1.272 / C^2}\right] \tag{2.14}$$

The drainage density is defined as the total length of streams of all orders contained in the basin's unit area:

$$D_d = (\sum L_x)/A \tag{2.15}$$

where L_x is the total length of the streams of order x. In common practice, the lengths are expressed in kilometres and the areas in square kilometres.

The basin relief, shown on maps by contours, can be described by the hypsometric distribution or the hypsometric curve. Figure I.2.20 shows a representation of relief and drainage network. The elevation ranges are shown by different marking.

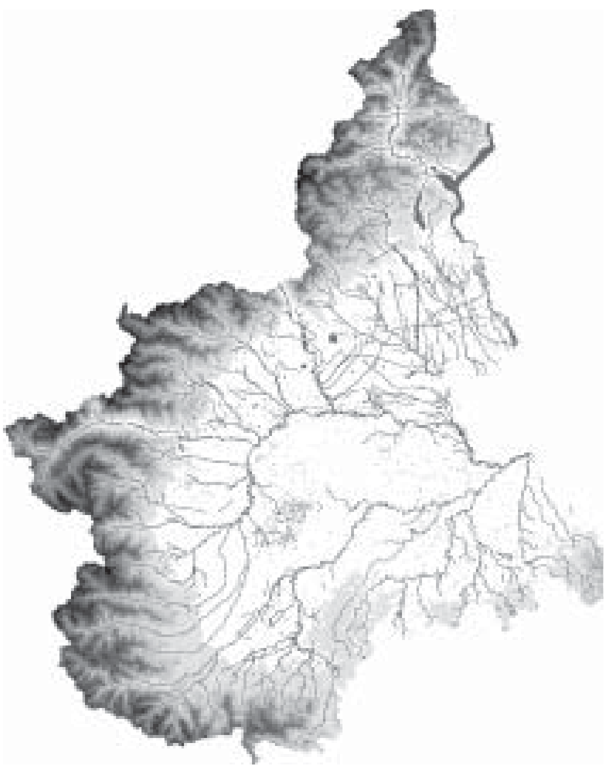


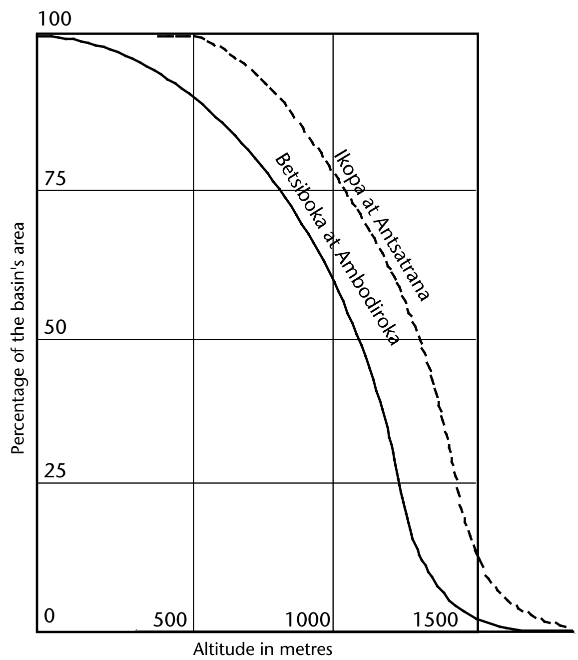
Figure I.2.20. Relief and drainage network
(Courtesy ARPA-Piemonte)

The hypsometric distribution gives the percentage (or fraction) of the basin's total area that is included in each of a number of elevation intervals. The hypsometric curve shows, on the ordinate, the percentage of the drainage area that is higher than or equal to the elevation that is indicated by the corresponding abscissa (Figure I.2.21). In practice, the cumulative distribution of area is obtained in a GIS or by planimetric calculation of successive areas between contours of elevation beginning with the basin's lowest point.

It is possible to calculate the basin's mean elevation by dividing the area under the hypsometric curve by the length of the ordinate corresponding to the whole basin.

The basin slope can be represented by several indices. The oldest, and perhaps still the most widely used, is the basin's mean slope S_m. It is determined from the basin contours by the formula:

$$S_m = z \sum l/A \tag{2.16}$$



Ikopa at Antsatrana		Betsiboka at Ambodiroka	
300–400 m ...	0.01	40–300 m ...	0.03
600–900 m ...	0.14	300–800 m ...	0.10
900–1 200 m ...	0.23	600–900 m ...	0.18
1 200–1 500 m ...	0.43	900–1 200 m ...	0.37
1 500–1 800 m ...	0.12	1 200–1 500 m ...	0.30
1 800–2 100 m ...	0.01	1 500–1 800 m ...	0.02

Figure I.2.21. Hypsometric curves
(Courtesy ARPA-Piemonte)

where z is the contour interval, $\sum l$ is the total length of all contours within the basin, and A is the basin's area. The difficulty and main source of error in estimating this characteristic lie in the measurement of $\sum l$. The contours are almost always very tortuous and their real length is not really characteristic of the role they play in calculating the index. Therefore, it may be necessary to smooth the irregularities keeping in mind the final results may be somewhat inconsistent and variable.

A mean slope can also be estimated by taking the basin's total difference in elevation and by dividing it by one of its characteristic dimensions. However, the distribution of slopes in the basin is neglected by this approach. One way of avoiding this is to derive the slope index from the hypsometric curve, which is a synthesis of the relief delineated by the contours, and to weigh the areal elements corresponding to the various elevation intervals by a non-linear function of the mean slope in each interval. Roche's slope index, also called the index of runoff susceptibility, meets these conditions. The notion of the equivalent rectangle (equation 2.14) is applied to each contour to transform geometrically the contours into parallel straight lines on the rectangle representing the entire basin (Figure I.2.22). If a_i and a_{i-1} are the elevations of two successive contours and x_i is the distance separating them on the equivalent rectangle, the mean slope between these two contours is taken to be equal to $(a_i - a_{i-1}) / x_i$, and the slope index is written by designating as $\tilde{n}_i$ the fraction of the basin's total area included between a_i and a_{i-1}:

$$I_\pi = \sum(\tilde{n}_i(a_i - a_{i-1}) / L)^{1/2} \tag{2.17}$$

The Roche slope index is as follows:

Basin	*Length of equivalent rectangle*	*Slope index*
Betsiboka at Ambodiroka	238 km	0.078
Ikopa at Antsatrana	278 km	0.069

When basins have a very low slope, for example, in the interior plains of North America, there may be closed sub-basins having no outlet to the main stream or significant portions of the basin that contribute to streamflow very infrequently. Under these circumstances the concept of an effective drainage area may be used. This is customarily defined as the area that would contribute to streamflow in a median year. Establishing the effective drainage area for a basin may require significant cartographic and hydrological analysis.

A basin's physical characteristics are essentially the soil types, the natural plant cover or artificial cover (crops), the land cover (for example, lakes, swamps, or glaciers), and the type of land use (for example, rural or urbanized areas, lakes, or swamps). They may also be expressed in terms of the basin's reaction to precipitation, this is, classes of permeability. These physical characteristics may be assembled as layers within a GIS.

The quantification of these characteristics requires definition of criteria and procedures for delineating

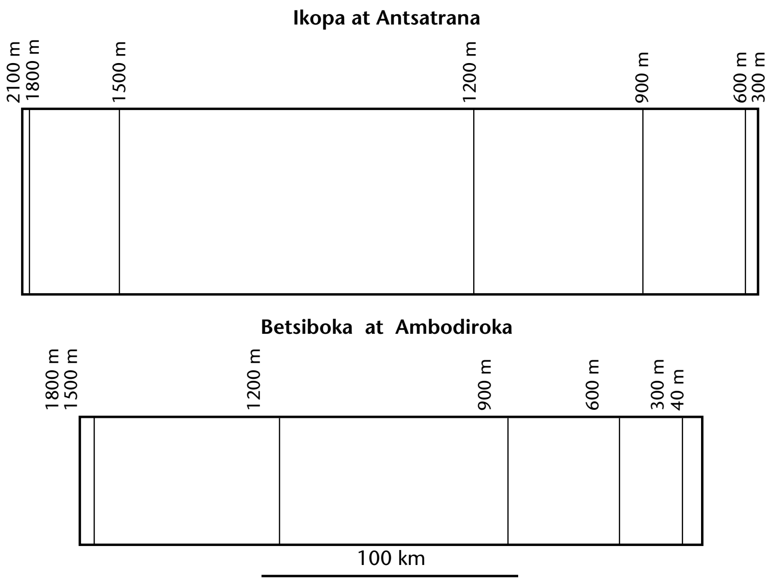


Figure I.2.22. Equivalent rectangles

the areas meeting these criteria. It then remains only to measure each of these areas and to express each as a percentage (or fraction). The tools for determining such distributions include GIS, normal and/or specialized cartography, aerial photography and remote-sensing with relatively fine resolution (pixels not to exceed some hundreds of square metres).

2.6.5.2 The grid

The formation of physiographical data banks, especially for the development of rainfall-runoff models with spatial discretization, leads to the division of the basin area based on systematic squaring or griding. Depending on the objective, the grid size may be larger or smaller, and may be measured in kilometres (1 or 5 km^2) or based on the international geographical system (1′ or 1° grid). GIS (2.6.7) have made interchanging between gridded and ungridded data a simple task once the initial databases have been assembled.

2.6.6 Volumetric measurements

Volumetric measurements pertain primarily to the definition of water and sediment storage. Evaluation of groundwater storage is covered by hydrogeology. It therefore will not be discussed here, nor will the estimation of sediment deposited on the soil surface. Surface storages are generally either the volumes of existing lakes or reservoirs, for which bathymetric methods are used, or the volumes of reservoirs that are being designed, for which topographical methods are used.

2.6.6.1 Bathymetric methods

Ordinary maps rarely give bathymetric data on lakes and reservoirs. The volume of an existing reservoir, therefore, has to be measured by making special bathymetric readings. Usually, this is done from a boat by using normal methods for sounding and for positioning the boat. The depths should be referenced to a fixed datum and a stage gauge or a limnigraph so that variations in stage can be monitored.

Depth measurements can be used to plot isobaths, and the reservoir's volume above a reference plane can be calculated through double integration (generally graphical) of the isobath network. One application of this method is sedimentation monitoring in a reservoir.

2.6.6.2 Topographical methods

Once the site of a dam has been fixed, the calculation of the reservoir's efficiency and management requires knowledge of the curve of volume impounded as a function of the reservoir's stage (stage-volume curve). To determine this relationship, ground-surface-elevation contours are needed throughout the area to be occupied by the future impoundment. This requires maps or topographical plans of the area on scales of between 1/1 000 and 1/5 000. If these are not available, maps on a scale of 1/50 000 can be used for preliminary design, but a topographical survey on an appropriate scale will be needed subsequently.

By using the contour map, planimetric measurements are made, in a GIS or manually, of the areas contained within the contours with the hypothetical reservoir in place. A plot of these areas versus their related elevations is known as a stage-area curve. The stage-volume curve is computed from the stage-area curve by graphical integration.

2.6.7 Geographical Information Systems

GIS are now ubiquitous in the fields of operational hydrology and water resources assessment. Many aspects of data collection and interpretation can be facilitated by means of GIS.

In network planning and design, the ability to map quickly and display surface water and related stations enables a more effective integration to take place. Network maps, showing basins or stations selected according to record quality, watershed, or operational characteristics, can be used for both short-term and long-term planning. The essential features of complex networks can be made very clear.

GIS techniques are being incorporated in hydrological models for the purpose of extracting and formatting distributed watershed data. Used in conjunction with digital elevation models or TINs (2.6.2), complete physiographic and hydrological depiction of basins can be readily accomplished.

Runoff mapping and interpolation is being carried out using GIS routines in many countries. The efficiency of handling large volumes of data means that more comprehensive and detailed maps, isolines and themes can be prepared. This represents a significant improvement to water resources-assessment technology, as map preparation is often time-consuming and expensive.

The interpretation of real-time data can also be facilitated through GIS. The thematic mapping of stations reporting over threshold amounts or digital indications of rainfall would obviously be very useful to both operational hydrology and forecasting agencies.

GIS systems are now available for standard computers in practical, low-cost formats. The main cost factor now resides in the areas of database compilation, and training and updating of technical staff.

2.6.8 Emerging technologies

The subsequent chapters of this Volume of the Guide deal with proven technologies that are commonly used in many parts of the world. However, as indicated above, new technologies are continuously evolving. This section provides some insight into several of these so that Hydrological Services may be kept aware of their possibilities.

2.6.8.1 Remote-sensing

In the field of hydrological measurements, two kinds of remote-sensing techniques are commonly used: active (by emission of an artificial radiation beam toward the target and analysis of the target response), or passive (by analysis of the natural radiation of an object).

In active methods, radiation may be high-frequency electromagnetic (radar) or acoustic (ultrasonic devices). The apparatus may be installed on the ground (radar, ultrasonic), on airplanes, or on satellites (radar). Active remote-sensing is usually done on an areal basis, but may also be used for point-oriented measurements (ultrasonic).

In passive methods, the radiation is electromagnetic (from infra-red (IR) to violet, and rarely ultraviolet). Most current applications are made by means of a multi-spectral scanner, which may be airborne, but is more frequently carried on a satellite. Passive sensing is always areal.

Radars are now used for quantitative precipitation estimates over a given area. Snow-water equivalent can be determined by measuring the natural gamma radiation from potassium, uranium and thorium radioisotopes in the upper 20 cm of soil under bare ground conditions and with the snowpack. Observations are made from a low-flying aircraft. Data are collected on a swath about 300 m wide and 15 km long. Results will be affected by ice lenses or liquid water in the snowpack, ground ice or standing water (Carroll, 2001). Microwave sensors, both airborne and satellite, have been used as well to monitor snowpack properties. RadarSat active radar has also been used to map the areal extent of wet snow.

Airborne optical devices (Lidar) are now used to determine topography more rapidly and, often, more accurately and at lower cost than conventional aerial photography. The resulting digital elevation model has applications in hydraulic and hydrological modelling and in determining glacier mass balance. Satellite Lidar altimetry has been used to obtain very good topography for military purposes and in research applications, but has not yet been commercialized. In the absence of national topographic data, the low-resolution global digital elevation model GTOPO30 with a horizontal grid spacing of 30 arc seconds (roughly 1 km) may be considered. The vertical accuracy of the data is about 30 m. This digital elevation model is also linked to the HYDRO1k package which provides a suite of six raster and two vector data sets. These data sets cover many of the common derivative products used in hydrological analysis. The raster data sets are a hydrologically correct digital elevation model, derived flow directions, flow accumulations, slope, aspect and a compound topographic (wetness) index. The derived streamlines and basins are distributed as vector data sets.

A further existing topographic data option is the 3 arc-second (90 m) digital elevation model produced by the Shuttle Radar Topography Mission. The data for most of the coverage area have been processed to level 1, which provides for an absolute horizontal accuracy of 50 m and a vertical accuracy of 30 m. The level 2 digital elevation model, currently available only for the United States, has a horizontal accuracy of 30 m and vertical accuracy of 18 m.

Other uses of remote-sensing in hydrology include sensing of near-surface soil moisture using airborne natural gamma or satellite passive microwave techniques and measurement of land surface temperature as a precursor to determining evapotranspiration. Leaf area index measurements use may also lead to remote-sensing of evapotranspiration. Remote-sensing of water quality also offers considerable promise as new satellites and sensors are developed. Water bodies that are affected by suspended sediment, algae or plant growth, dissolved organic matter, or thermal plumes undergo changes in spectral or thermal properties that may be detected by airborne or satellite sensors (UNEP/WHO, 1996). Some use has been made in the measurement of water body areas and the extent of flood inundation using RadarSat active radar. Aside from the requirement to calibrate airborne or satellite sensors, there is also a need to ground-truth the remotely sensed data to ensure that remotely sensed values represent in situ values.

2.6.8.2 Hydroacoustic methods

Hydroacoustic methods hold considerable promise for hydrological data acquisition. Acoustic signals may be used to identify the interface between two dissimilar media or to explore the characteristics of a single medium. For example, echo sounders are used to define the streambed in hydrographic surveys or to sense the distance to the water surface when mounted in or above a stream. Results can be very satisfactory provided careful attention is paid to calibration of the instrument. Acoustic current meters that determine water velocity by measuring the Doppler shift of acoustic energy reflected from water-borne particles have been used for a number of years.

The 1990s saw the development of the Acoustic Doppler Current Profiler (ADCP), an instrument that uses acoustic energy to determine streamflow from a moving boat. The instrument consists of four orthogonal ultrasonic transducers fixed to a moving boat. As the boat traverses a river the instrument measures the frequency shift of the reflected signals and uses trigonometry to produce velocity vectors in uniformly spaced volumes known as depth cells. The velocity of the boat is removed in computer processing and, with the channel geometry also defined by the instrument, the streamflow along a river transect can be calculated. This technique has been used successfully to measure relatively large streams. More recently, efforts have been directed to the measurement of smaller streams (under 2 m depth) using hand-held or in situ instruments.

Acoustic devices have also been developed to examine lake dynamics or to determine the density and material characteristics of bottom and sub-bottom sediments. Ultrasonic flowmeters are reviewed in Chapter 5.

2.6.8.3 Risk reduction for personnel

There are inherent dangers to personnel involved in acquiring hydrological data under difficult conditions. These dangers are perhaps best exemplified by the challenge of measuring streamflow under flood conditions. High velocities, debris or ice may threaten the life of persons attempting to make the measurement. Efforts are therefore underway to automate the measurement process through use of robotics and other procedures. One early approach to improved safety was the development of stream-gauging cableways that could be operated from the river bank. Another was the moving boat method, which reduces the time required for a discharge measurement, but still requires exposing personnel to the hazard.

One current concept calls for an automated, unmanned boat equipped with an Acoustic Doppler Current Profiler the position of which is monitored by use of the global positioning system. Measurements can therefore be made under high hazard conditions with minimum exposure of personnel to the hazard. Another approach uses a hand-held radar to measure surface velocities and, where channels are unstable, ground-penetrating radar to define the channel cross-section. The radar device produces an accurate surface velocity, which must then be related to mean velocity, while the ground-penetrating radar moving along a bridge or cableway produces an accurate cross-section.

Other risk reduction efforts include the decommissioning of water-level sensors based on mercury manometers and the increased use of satellite telephones as a means of maintaining contact with field parties in remote areas.

2.6.9 Staff training

Whatever the level of technical sophistication of a data-collection authority, the quality of its staff will always remain its most valuable resource. Careful recruitment, training and management is the key to attaining and maintaining the appropriate personnel.

WMO has published a set of *Guidelines for the Education and Training of Personnel in Meteorology and Operational Hydrology* (WMO-No. 258). UNESCO has published a document on *Curricula and Syllabi in Hydrology* (UNESCO, 1983). With respect to data collection and processing, employee education, although costly and time-consuming, can be a sound investment that results in greater productivity and effectiveness. A carefully structured training programme is essential for all personnel engaged in data collection because they are in a strong position to influence the standard of the final data. Formal training should aim at providing both a general course in first principles, plus training modules to teach in-house procedures. All material should be relevant and current. The Canadian hydrometric technician career development programme (HOMS component Y00.0.10) provides one national example (WMO, 2000). Volume II, Chapter 2, provides additional information on different aspects of training in hydrology.

Where processing is not carried out by the data collector, it is important that data processors be trained in data-collection techniques to ensure that data are processed according to the intent of the collector. It is a good practice to give processing staff periodic field experience to build a physical association with the data and their origins. Such knowledge on the part of the processor can allow interim interpretations of incorrectly presented data, pending confirmation from the collector. It is essential to establish the principle that the person collecting the data has the primary responsibility for its quality. One method of honouring this principle is to involve the collector in the processing as much as possible, and to ensure that feedback is obtained by returning the published data to the collector for assessment. At the processing stage, staff should recognize that they also have a responsibility to maintain the quality and integrity of the data.

Data processing is often routine in nature and well suited to the application of automation and technology. For this reason, it is important that special attention be given to the care of human resources, and that the system be structured to foster interest, involvement, professionalism and a sense of achievement. Data-processing staff should be given the opportunity to contribute ideas that may increase the effectiveness of the processing system.

Staff safety is also an integral component of any profession, and the duties undertaken by data collectors and processors require the establishment of safety standards. These are primarily discussed in Chapter 8. However, the possibility of repetitive strain injury in data-processing staff can often be caused by routine and the repetitive nature of some aspects of their jobs. This problem should be addressed from both a staff safety and a management point of view.

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